Optimization of mechanical mass production and energy management for a paper mill with an integrated CHP plant

Kristo Helin

School of Engineering

Thesis submitted for examination for the degree of Master of Science in Technology.

Helsinki 26.10.2015

Thesis supervisor:

Prof. Risto Lahdelma

Thesis advisor:

D.Sc. (Tech.) Anssi Käki

Aalto University
School of Engineering

AALTO UNIVERSITY
SCHOOL OF ENGINEERING

ABSTRACT OF THE
MASTER'S THESIS

Author: Kristo Helin

Title: Optimization of mechanical mass production and energy management for a paper mill with an integrated CHP plant

Date: 26.10.2015 Language: English Number of pages: 7+46

Degree programme: Energy and HVAC Technology

Major: Energy Technology Code: K3007

Supervisor: Prof. Risto Lahdelma

Advisor: D.Sc. (Tech.) Anssi Käki

The pulp and paper industry is facing global competition, where companies are working to lower their production costs. Energy consumption plays an important role in these costs. There is much interest into lowering the electricity costs of mills through demand side management. This Thesis is a case study of a mechanical pulp and paper mill with integrated CHP production. The case site is modeled with focus on the critical dependencies between pulp, paper, and CHP production. The purpose of the model is to analyze the mill's capacity of demand side management, and the total costs of executing regulating power bids in the mill site.

The production scheduling of mechanical mass is studied through a mixed integer linear model. The model is based on the processes of the mill site, considering the balances of steam, electricity, heat, and mechanical mass. Paper production scheduling is not in the scope of the model. The model is utilized to calculate the increase of production costs in case a regulating power trade is made.

The model creates an optimal mechanical mass production schedule for a 24 hour period. It is then used to modify that schedule based on a hypothetical regulating power bid that is accepted on the first hour of the modeling period. The cost difference between the resulting two schedules is calculated, denoting the real cost of regulating in that scenario. This analysis is repeated for a number of real periods in terms of electricity price and district heating demand.

The model generates realistic production schedules of mechanical mass. Up-regulating power trades are found to cause moderate costs, but there is significant variation. It is noted that the co-planning of the mill and power plant plays an important role in the results. Its design allows the model to be used for various purposes in addition to what is presented in this Thesis.

Keywords: energy management, paper production, pulp mill, mixed-integer optimization, scheduling, CHP

AALTO-YLIOPISTO
INSINÖÖRITIETEIDEN KORKEAKOULU

DIPLOMITYÖN
TIIVISTELMÄ

Tekijä: Kristo Helin

Työn nimi: Mekaanisen massan tuotannon ja energiahallinnan optimointi paperitehtaalle, jolla on integroitu CHP-voimalaitos

Päivämäärä: 26.10.2015 Kieli: englanti Sivumäärä: 7+46

Koulutusohjelma: Energia- ja LVI-tekniikka

Pääaine: Energiatekniikka Koodi: K3007

Työn valvoja: prof. Risto Lahdelma

Työn ohjaaja: TkT Anssi Käki

Sellu- ja paperiteollisuus on globaalissa kilpailutilanteessa, jossa yritykset pyrkivät alentamaan tuotantokustannuksiaan. Energian kulutuksella on suuri rooli näissä kustannuksissa. Sähköenergiakustannusten alentaminen kulutusjouston avulla herättää paljon kiinnostusta. Tässä diplomityössä esitellään case-tutkimus mekaanista massaa ja paperia valmistavasta tehtaasta, jolla on integroitu CHP-voimalaitos. Kohteena oleva tehdas voimalaitoksineen mallinnetaan, keskittyen tärkeimpiin riippuvuuksiin massan, paperin ja energian tuotantoprosessien välillä. Tavoitteena on analysoida tehdaskokonaisuuden kapasiteettia kulutusjouston tekemiseen sekä säätösähkötarjousten toteuttamisen kustannuksia.
Mekaanisen massan valmistuksen aikataulutusta tutkitaan lineaarisen sekalukuoptimointimallin avulla. Malli perustuu tehdaskokonaisuuden prosesseihin, joista huomioidaan taseet höyrylle, sähkölle, lämmölle ja mekaaniselle massalle. Paperintuotannon aikataulutus ei kuulu mallin piiriin. Työssä esitetään, miten mallia voi käyttää säätökaupan aiheuttamien lisäkustannusten laskemiseksi.
Mallin avulla luodaan optimaalinen mekaanisen massan tunneittainen tuotantoaikataulu vuorokauden jaksolle. Tätä aikataulua muokataan edelleen mallin avulla kuvitteellisen säätösähkötarjouksen perusteella, joka hyväksytään mallinnusjakson ensimmäisellä tunnilla. Vertaamalla tuloksina saatujen kahden aikataulun kustannuksia voidaan arvioida säädön todellinen kustannus. Tämä analyysi toistetaan useissa eri tilanteissa todellisilla sähkön hinnoilla ja kaukolämmön tarpeilla.
Malli tuottaa realistisia aikatauluja mekaanisen massan tuotannolle. Ylössäätökauppojen todetaan aiheuttavan kohtuullisia kustannuksia, mutta vaihtelu on suurta. Huomataan, että paperitehtaan ja voimalaitoksen yhteissuunnittelu on tärkeässä roolissa tuloksissa. Mallin rakenne mahdollistaa sen käyttämisen tässä työssä esitettyjen lisäksi myös muihin tarkoituksiin.

Avainsanat: energiahallinta, paperin tuotanto, sellutehdas, sekalukuoptimointi, aikataulutus, CHP

Preface

This Thesis was written at UPM Energy. It was written to the Department of Energy Technology of Aalto University School of Engineering. I thank Head of Department, Prof. Risto Lahdelma for supervising this work. I thank my instructor D.Sc. Anssi Käki for his extensive support and guidance during my thesis work. I also thank Prof. Sanna Syri and M.Sc. Behnam Zakeri of Aalto University, and my colleagues Juha Haromo, Katja Havikari, Sari Siirtola, and Timo Pitkänen for their participation in this work.

I am grateful to my friends and family for their support over the course of my studies and this work. I want to thank my friend Tuomas Ollikainen for his presence in this process, as well as my other peers at the university.

Helsinki, 26.10.2015

Kristo Helin

Contents

Abbreviations

adt	Air-dried tonne (containing at most 10 % of water)
CHP	Combined heat and power production
DH	District heat, district heating
DSM	Demand side management
GW	Groundwood
MILP	Mixed integer linear programming
MINLP	Mixed integer nonlinear programming
PGW	Pressurized groundwood
PM	Paper machine
PRV	Pressure reduction valve
TMP	Thermomechanical pulp
TSO	Transmission system operator

1 Introduction

The mitigation of the climate change is a common goal in the European energy policy [1]. The importance of actions limiting global warming is recognized also globally [2]. Many countries have adopted policies to encourage the increase of renewable energy in energy production [3]. Some variable renewable energy technologies are becoming common around the world, including wind and solar electricity. High penetration levels of variable renewable energy will require additional flexible resources in the energy system [4]. The trend of growing variable renewable electricity production is visible also in Finland, where the installed capacity of wind power grew 40 % from 450 MW during the year 2014 [5].

In the Nordic countries, matching the demand and supply of electricity is managed through several different electricity markets on different timescales [6]. On all of the markets it is possible for producers and consumers to manage their use of capacity to minimize total costs or maximize profits from electricity trading [7]. Flexibility of electricity consumption by the price of electricity is referred to as demand side management (DSM) [8]. This is beneficial to both the market player and the power grid that relies on the stability of production and consumption of electricity. In the Finnish energy-intensive industry there is notable unused potential for DSM [7].

The focus of this Thesis is in industrial DSM. A mathematical model is created that makes it possible to study the ability of a case paper mill site to participate on different electricity markets. The case site operates many loosely coupled and energy-intensive processes. This makes it a good example of an industrial plant where there is high potential for DSM, but it is difficult to assess due to the complexity of the process interdependencies.

The transmission system operator (TSO) of Finland, Fingrid Oyj, is working to increase the amount of DSM in the Finnish electricity market to strengthen the balance between the consumption and supply of electricity. Industrial consumers are of special interest. Several reasons can be found for this: i) industrial loads are large, in particular in process industries like paper, chemical, and metal industries, ii) electricity intensive processes are often adjustable, and iii) participation in grid regulating could reduce the operating costs of many industrial consumers.

From the perspective of the TSO, short-term DSM with reaction times from 15 minutes down to 5 seconds is of special importance [7]. The participation on these markets may, however, not be economically feasible for many process industries. Participation may require additional investments in technology, and many continuous processes work better if they run at a constant rate without stops [7, 9]. The main objectives in production are also often related to customer needs, not driving down energy costs, let alone participating in short-term electricity markets. Moreover, the skills and knowledge needed for successful action on these markets are not always among the key competences of the operators of a production plant. Optimal sizing, pricing, and timing of possible participation on short-term electricity markets require careful market analysis and mathematical modeling in both planning and operation phase.

1.1 Objectives

This Thesis presents a model that can be used for assessing the DSM capabilities of a pulp and paper mill with an integrated combined heat and power (CHP) plant. The model optimizes production plans for mechanical mass and CHP production considering the key processes of the case site. The model is extended for regulating bid scenarios, where mechanical mass production lines are halted or started after optimization, i.e. after electricity purchases from the spot market are made. This allows the calculation of cost of regulating power for these lines. In short, this Thesis seeks answers to the following questions:

- How much flexibility is there in mechanical mass production? In particular, how much flexibility do mechanical mass storages allow in the case site?
- How can the mill site operation be optimized as a whole, including CHP production? What are the critical dependencies between different processes that impact mill operations and flexibility with regard to energy management?
- What is the total cost of executing regulating power bids in the case mill site?

With the help of the model, the case company can better evaluate the economic potential of DSM. The results can also help decision makers like the TSO and authorities understand how DSM can be seen from an industrial player's point of view. The model can be extended and modified to various directions and analyses to better match these goals. Due to this flexibility, the model has also practical relevance to the pulp and paper industry, and other energy-intensive process industries. The model, or parts of it, can be used to assess the capability of any processing plant to control their energy consumption in a way that minimizes the cost of energy, while fulfilling other process requirements.

1.2 Thesis structure

The structure of this Thesis is as follows. First, in Section 2, literature is reviewed about the lowering of energy costs of a pulp and paper mill. Then, in Section 3, the case site of this work is described along with the typical processes of a general mill site of the same type. In Section 4, different electricity markets are presented that are relevant to this Thesis. In Section 5, a model is described that optimizes the mechanical mass production of the case mill site. This model is extended in Section 6 to model regulating power scenarios. Results of the model are presented and analyzed in Section 7. Section 8 concludes.

2 Background

Increasing competition amongst pulp and paper mills has driven the industry into a situation where lowering production costs is a necessity. Various solutions have been developed, including i) energy efficiency solutions, ii) better utilization of side products, iii) improved production scheduling, iv) improved energy management, and v) joint optimization of energy management and production scheduling. This work focuses on the last, mainly the scheduling of mechanical pulp production by thermomechanical pulping and grinding.

2.1 Energy efficiency

Extensive effort has been made to reduce the energy consumption of pulp and paper production. Ruohonen and Ahtila [10] analyze an existing thermomechanical pulp (TMP) and paper mill using a pinch analysis based approach. They conclude that the steam produced by the TMP line is not utilized in the case site to the extent that is possible. By optimizing the use of steam, production of steam in the power plant could be reduced. Ruohonen et al. [11] analyze data from an existing groundwood (GW) and pressurized groundwood (PGW) pulp and paper mill. Using a simulation model they consider four different uses of secondary heat in the mill. The alternatives were heat exchanger network retrofits (to reduce additional heating needs), drying of bark, drying of sludge, or both of the last two. All considered options are found to reduce the CO_2 emissions of the mill. Both of the mentioned studies concentrate on the heat and steam use in the mill, rather than technical details of the grinding or refining equipment. Energy conservation of the Chinese pulp and paper industry is studied by Lingbo et al. [12]. They estimate that in 2010 the cost-effective fuel conservation potential of the industry was 27 % of total fuel used. The corresponding technical potential was 38 %. Almost a quarter of the world's total paper production in 2010 was done in China. According to the authors, most of the potential for savings in mechanical pulping were related to heat recovery in TMP mills. GW processes are not accounted for.

2.2 Side products

The overall energy efficiency of a mill site may be improved by additional production that utilizes secondary heat from the main production. The pulp and paper industry is going through a transitional period, where paper mill sites have begun producing secondary products [13]. Carefully selected products can increase both the profitability and the overall energy efficiency of the mill. These products can be for instance electricity, dried bark, biofuels, or district heating (DH). It is common for paper mill sites to contain their own CHP power plant, which makes selling electricity and district heating a natural choice [14].

2.3 Production scheduling

Paper mill sites that produce thermomechanical pulp are major consumers of electricity. These sites typically buy most of their electricity from a spot market. Companies utilize DSM to minimize their absolute costs of electricity. In this type of operation, the aim is not to reduce the overall consumption of energy, but to consume it at the right time with respect to the price of electricity [15]. This can mean, for example, that load is shifted from price peaks to valleys, or clipped from consumption completely.

This Thesis focuses on DSM of a site with TMP and GW production, paper production and an integrated CHP plant. The scheduling work of such a plant is a complicated task. It is, however, common in the industry to do planning and scheduling manually at the site [15–18]. This includes planning of the operation of the mill site including paper production, pulp production, and energy production. Iterations between layers of planning may be done to find an appropriate and feasible production plan for the whole site [17]. Companies may use advanced tools for planning the cutting of paper reels, but conversely rely on spreadsheets and planner expertize alone for overall planning of production rates and sequences [16]. In this type of operation, feasibility of the final schedule may be placed over optimality, leading to suboptimal production plans and schedules [16–18].

Systems and models for aiding the task of production planning and scheduling have been developed. Figueira et al. [16] develop a decision support system for pulp and paper production, that assists a planner in creating an optimal lot size and schedule. In their analysis, they compare an optimized plan with a manual plan created in the same system. They conclude that the optimization resulted in the reduction of some percentages in backlog, setup costs, and inventory. The manual plan resulted in 2 % of additional production.

Figueira et al. [18] have created a model for the short-term production planning and scheduling of a paper mill. Their model is more technical than others mentioned here, as it considers the material flows of pulp, black liquor, and paper in some detail. Variables and parameters such as current paper grade and average trim loss are considered. The authors do not consider variable electricity prices in their model. The model concerns a hcal pulp and paper mill. A type of Variable Neighborhood Search algorithm is proposed, and presented, for tackling large Lot Size and Scheduling problems.

2.4 Energy management optimization

The optimization of energy management in pulp and paper mills with a CHP power plant is studied by Sarimveis et al. [19]. They develop a power plant model that optimizes the production of steam and electricity for the needs of a pulp and paper mill. Rong et al. [20] present a unit decommitment algorithm for CHP production planning. They present a model for estimating the operating region of a CHP plant. Jüdes et. al present a mixed integer nonlinear programming (MINLP) model for the partial-load operation of a cogeneration plant. The plant is a gas-fired combined cycle plant with steam extraction.

2.5 Joint optimization of scheduling and energy management

Ait-Ali [21] presents a mathematical model where production scheduling and energy management are jointly optimized for a pulp and paper mill. The optimization of the two tasks is decomposed, and the decomposition is concluded to produce equally good results to optimization without decomposition. Production planning and scheduling utilizing a problem decomposition method has also been discussed by Figueira et al. [18]. Their work is about steel production, which is a capital and energy-intensive industry similar to mechanical mass and paper production. According to the authors, planning and production scheduling is typically hierarchical in nature, and the maximum throughput of the mill is sought.

For manual hierarchical planning between the pulp and paper production it is typical for backlogging and inventory costs to be improperly weighted [18]. Merkert et al. [15] write about integrated power production in mechanical pulp and paper mills, that "commitments on energy market operations and changing energy prices can cause high variations to the hour-to-hour production costs of pulp, especially if last-minute changes in the pulp production schedule are accepted." The authors also note that late changes in production schedules or unplanned events increase pressure for late changes also in pulp production plans and deviations from intended energy balances.

If a TMP plant has more production capacity than what is required for the paper mill or selling, it is possible to schedule pulp production against volatile electricity prices [15]. The schedule can be optimized to minimize the energy costs or maximize the profits from excess energy by utilizing intermediate storage capacity. The capability to schedule mass, paper, and energy production is dependent on the flexibility of the mill site processes. Storage of primary, secondary, and side products of processes create buffers between production stages. A high capacity of these buffers lower the degree of coupling between production stages, and thus increases the overall flexibility of the system [15].

Overall, there is abundant literature on both optimal production planning and energy management in pulp and paper production. Optimization in these areas is sophisticated and often considers detailed information about the case site. However, the joint optimization of both production planning and energy management is much less studied. Moreover, in the few studies about the subject, the studied systems are highly simplified. This Thesis offers insight into the joint optimization of mechanical pulp production and energy management in a model with a more detailed consideration of pulp and paper production.

3 Case site

In this section, the case site is described briefly. The site is a large pulp and paper mill located in Finland. A simplified illustration of the mill site processes is shown in Figure 1.

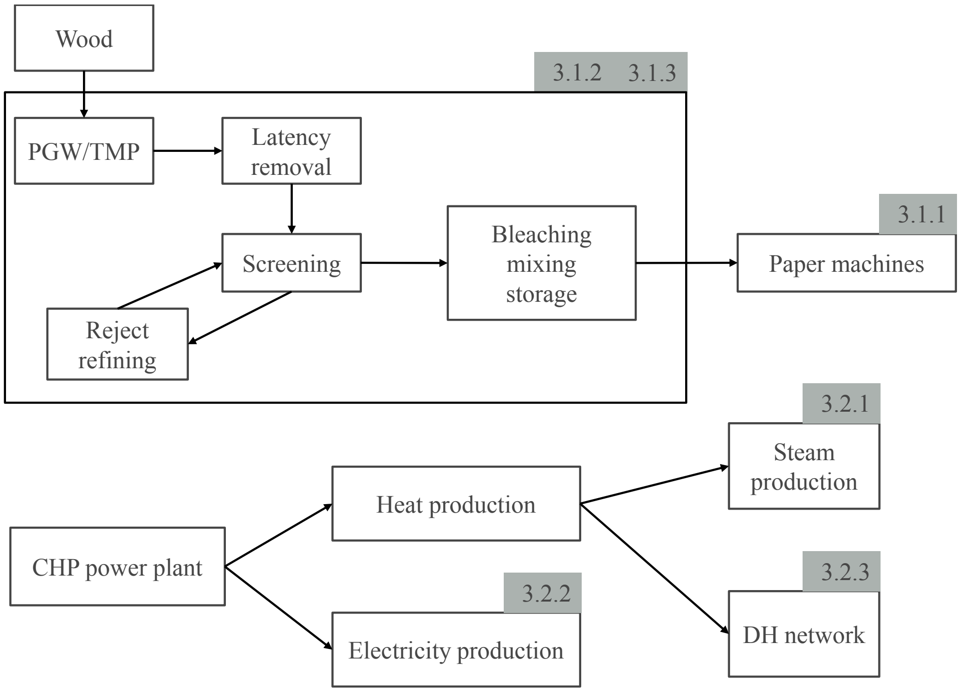

Figure 1. An illustration of the case mill site. The grey boxes indicate the section describing the major processes in more detail.

3.1 Paper mill

In the following, the main processes of the case site pulp and paper mill are described. The case site has three production lines for TMP production, two lines for GW production, and three paper machines (PM).

3.1.1 Paper machine

In a paper machine, a suitable combination of different pulp types are dosed onto a thin web in the headbox of the machine. This mass forms the stock suspension. The stock goes through various phases of rotating cylinders, which are used to remove water from it first mechanically and then by heating. During this process the actual paper is formed. If there are losses in the process, the waste material, which is referred to as broke, is processed, stored, and reused along with new prime pulp. [22]

Considerable amounts of steam is consumed by the paper machine. The steam is used to heat the cylinders in the drying process. It is also for heating the stock suspension in the press section, to increase the amount of mechanically removed water. Heat recovery is also implemented in paper machines, as the total amount of recoverable heat from the process can surpass 50 MW. [22]

3.1.2 Thermomechanical pulp

In thermomechanical pulping wood fibers are separated from each other by mechanical force. Wood chips are fed from the middle to between two opposing rotating discs of a refiner. The blades of the discs separate the wood fibers from each other. The result of this process is referred to as thermomechanical pulp. The process is energy-intensive with a single refiner consuming 10–30 MW of electric power. A single processing line can have 1–3 refiners, depending on the type and design of the machinery. A TMP process produces large amounts of steam. Water in the wood, both natural and from preprocessing, evaporates due to the frictional forces of refining. This latent heat is recovered in a heat exchanger and used in other processes as steam. Normally around two thirds of the refining energy can be recovered as clean steam. [22]

After being refined initially, the pulp goes through three notable steps. i) In latency removal the pulp is treated in a tank where its curled fibers straighten partially. ii) In screening and reject handling pulp is screened for unrefined fibre bundles. If the pulp does not pass the screening, it is refined again until it passes the screening. iii) In bleaching pulp is treated with either a ditionite bleaching process (less than 60 minutes in low consistency) or a peroxide bleaching process (1–4 hours in high consistency). Many different pulp qualities for different types of paper can be produced by altering the screening requirements, and bleaching reaction time and chemicals. [22]

3.1.3 Groundwood

Groundwood is produced in a grinding process. In grinding, debarked and cut-to-length spruce logs are pressed sideways against a rotating cylinder, the grinding stone. If the process is pressurized, the term pressurized groundwood is used. Pressurization makes it possible to increase the temperature of the process, which aids in softening the lignin of the wood. [22]

Steam is not typically produced in the GW/PGW processes, even though it would technically be possible. Latency removal of GW takes about 20 minutes. Similarly to TMP, different pulps can be created through different screening, reject handling, and bleaching parameters. [22] The case site utilizes the GW process.

3.2 Powerplant

The CHP plant produces electricity and steam for the mill site, and DH for the surrounding city. It also produces electricity to the market. The plant utilizes biomass, oil, and coal.

The CHP plant is co-owned by different parties. The model described in this work is based on i) the design of the power plant as a whole, ii) the production of steam and electricity that is the mill site's share of production, and iii) the DH production of the plant. DH is considered because of its effect on the power plant production. This notion about co-ownership and its effects are not repeated later in this work. Instead, the plant's production is seen to only include the mill site's share and district heating.

3.2.1 Steam production

The power plant produces middle pressure (10 bar) and low pressure (3 bar) steam for the paper mill. Both pressure levels of steam are generated in the TMP processes. Low pressure steam is also purchased from and sold to external companies.

The power plant typically operates with either one or two boilers. This varies depending on the season and maintenance needs. One of the boilers consumes oil and biomass as fuels, the other can additionally utilize coal. There is a single back pressure turbine in the power plant. The exhaust steam from the turbine is used for district heat production. There are two pressure extraction levels in the turbine, which are used to trade off electricity production for process steam. Extracted mass flows can be controlled within limits set by turbine design.

Both middle and low pressure steam can be produced from high pressure steam (ca. 110 bar) through pressure reduction valves (PRV). In line after the PRVs there are desuperheaters that add water to the pressure reduced stream. Additional water lowers the steam temperature while adding to the mass flow of stream.

Steam production is based on the needs of the paper mill. Steam is produced to steam bars, which balance out small variations in its production and consumption. Moreover, the system includes two steam accumulators that offer an additional buffer for short term variations in both production and consumption of steam. They can also be used to reduce middle pressure steam to low pressure steam, as there is not a PRV between these pressure levels.

Steam can be vented to outside air at will. This may come into question for example in times of very high electricity prices. During such time, the economically optimal electricity production may force more steam production than what is consumed by the paper mill. In addition, the paper mill production may be at halt during especially high electricity prices, further increasing the amount of vented steam. Steam produced by the TMP processes may also have to be vented, if the steam is not used in paper machines.

3.2.2 Electricity production

The power plant's production capacity for electricity is remarkably smaller than the typical consumption of the paper mill. The rest of the required electricity is purchased from the grid. If electricity is to be sold on the market, the mill must halt most of its processes. The power plant operation plan is made each day for the following day according to the needs of the paper mill and the forecast price of electricity.

3.2.3 District heat production

The case mill site power plant is the only DH provider in the city, which means that the consumption must always match production. Production of DH can be fulfilled in five complementary heat exchangers: i) the condenser of the turbine exhaust steam, ii) condenser of steam from an extraction point at less than 1 bar absolute pressure, iii) a condenser of steam from the low pressure steam bar, iv) an additional cooler of DH water (operated with outside water), which can also be used for small scale electricity production when the DH water temperature is much higher than required, and v) a DH accumulator, which creates a buffer against variations in production or consumption.

4 Electricity market in the Nordic countries

Trading of physical electricity (trading that leads to the delivery of electric power) is done in several markets of different timescales. The ones relevant to this Thesis are the Elspot market, where trading happens once daily for each hour of the following day, the Elbas market, where trading happens hourly, and the regulating power market, where a player can offer capacity for sale to balance the consumption and supply in the electric grid. The markets, in the mentioned order, are referred to elsewhere in this work as the spot market, the intra-day market, and the regulating power market. In this section, the main concepts of the markets are described. The operation of the mill site in the power market is also described.

4.1 Elspot

Elspot of Nord Pool Spot is the main power market in the Nordic countries. A total of 361 TWh of electricity was sold in the Elspot market during the year 2014 [23]. Bids to buy and sell electricity are left every day for each hour of the following day, and they are processed in a closed auction. The bids are conditional bids to buy or sell if the market price is lower (or equal) or higher (or equal) to the price requirement of the bid, respectively [24]. Each bid consists of at least two price-volume combinations: The greatest and lowest volume and their respective price limits. Bids made by one party can only be either to buy or sell electricity on any single hour. The price of electricity for each hour is the price that balances consumption and supply.

In addition to hourly bids, multi-hour bids called block offers can be made. They are bids of at least four consecutive hours. The block offers are accepted if the average cost of electricity over the whole block fulfills the requirement of the offer. If the acceptance of a block offer would alter the price of electricity in the whole market so that the block would not be accepted with the new price, the block is rejected. [24]

The whole Nord Pool Spot market area is divided into several bidding areas. A common system price of electricity is calculated regardless of electricity transfer capacities between these areas [25]. If the transfer capacities challenge the viability of the auction, the appropriate bidding area prices will be recalculated by predefined rules [24]. Otherwise the system price is the common price for the whole market area.

4.2 Elbas

Elbas is an intra-day market for trading power, operated by Nord Pool Spot. It supplements the Elspot market and helps market players match the consumption and supply in favor of both the players and the grid. Elbas is a continuous market in which trading takes place every day on every hour until one hour before delivery. In the Elbas market prices are set based on the first come, first served principle, where bids to buy and sell are matched immediately [25]. Block offers can also be left in the Elbas market [24].

4.3 Regulating power

The Nordic countries have a common regulating power market managed by the TSO's, to regulate the power balance of the electric grid. Regulating power bids of up- or down-regulation can be submitted for all resources which can implement a power change of at least 10 MW in 15 minutes [26]. The power change must be available for the duration of one hour. A bid can be either an increase or a decrease in either production or consumption of electricity, but not a combination of the mentioned. A price limit is set for all bids (€/MWh). Bids must be submitted to the TSO at least 45 minutes before the appropriate hour [26].

Regulating power bids are accepted in the order that is the most economic for the TSO accepting the bid. In normal situations bids are accepted in the order of price as long as there is still mismatch between production and consumption for the hour. The final price paid to regulating parties, however, always matches the highest price paid to any party on that particular hour. The final prices for both up- and down-regulation are published only after the regulated hour. [24]

4.4 Case site on the electricity market

The paper mill site production is planned hierarchically. Paper production goals are set by the need of output, mechanical mass production is planned by the needs of the paper machines, and power plant operation is based on the need of steam and district heating, and the price of electricity.

The mill site purchases electricity from the Elspot market to cover its planned production for each day. For protection against peaking prices of electricity, block trading is done. If the Elspot price is higher than a set limit, a block is sold and a part of the planned paper production is cancelled. The block volume and price limit may be changed depending on the current production and its priority. Trading is handled centrally by the case company control center according to the needs of the mill site.

Production of paper and mechanical mass occasionally require maintenance breaks that may be sudden or planned hours ahead. In these cases, if the deviation from planned electricity consumption is great, the control center is contacted to inform them of the coming deviation. Also in normal operation, there is imbalance between the planned and realized electricity consumption of processes. The control center handles hourly balancing, operating on the Elbas market as needed. The control center also handles regulating power bids in behalf of the mill site.

5 Optimization model

In this section, the modeling of the pulp and paper mill and the power plant is explained. The model is a mixed integer linear programming (MILP) optimization model, minimizing the cost of production when paper machine schedules and the forecast price of electricity are given. The result is a production plan for mechanical mass, that considers power plant production of electricity, steam, and DH, purchases of steam and electricity, and the schedule of paper production. The modeling period is 24 hours with a timestep of one hour. An illustrative overview of the model is presented in Figure 2.

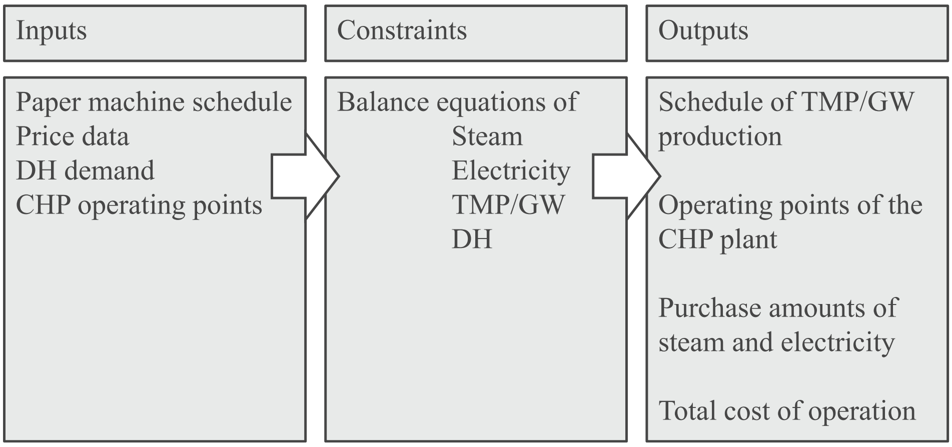

Figure 2. An illustrative overview of the model.

The parameters, variables and sets used in the model are listed in Sections 5.1–5.3. In the notation, the superscript is reserved for indices, while the subscript contains descriptions of the variable. For example, $M^{s,i}_{\text{stor,total}}$ denotes mechanical mass (M) total storage (stor, total) for each storage tower (s) and on each timestep (i), and $M^{i,s_1\to s_2}_{\text{move}}$ means mechanical mass moved from storage (s_1) to storage (s_2) during each timestep (i). The index i denoting time step is not repeated in the text later on, but it will be visible on all appropriate parameters and variables.

5.1 Parameters

The following parameters are used in the model:

A_{GW}	A large positive integer, auxiliary parameter for GW scheduling
DH^{i}_{req}	District heat requirement on hour i (MWh/h)
DH_{ccost}	Cost of additional cooling of DH water (€/MWh)
E^{j}_{cons}	Electricity consumed by application j (MWh/h)
E^{i}_{price}	Price of electricity (€/MWh)
F_{eff}	Efficiency of burning fuel in boiler
F_{price}	Average price of fuel (€/MWh)
$GW^{l_{GW}}_{\text{stones,min}}$	Minimum number of stones in state ON for a GW line to be ON

$K_{\text{CHP}}^{k,Dc}$	Operating point (k) data for the power plant
$M_{\text{changerate}}^{s}$	Maximum allowed change in storage per timestep (adt)
M_{cons}^{j}	Mechanical mass consumed by application j (adt)
M_{delay}^{s}	Amount of time steps a unit of mass must remain in tower s (integer)
M_{end}^{s}	Storage tower surface level after last timestep
M_{start}^{s}	Initial storage tower surface level, $M_{\text{start}}^{s} \in [0,1]$
M_{prod}^{j}	Mechanical mass produced by application j (adt)
$M_{\text{rec}}^{s_1,s_2}$	Recipe for mass moved to s_2 from s_1, $M_{\text{rec}}^{s_1,s_2} \in [0,1]$
$M_{\text{stor,max}}^{s}$	Maximum allowed storage of mechanical mass for tower s (adt)
$M_{\text{stor,min}}^{s}$	Minimum allowed storage of mechanical mass for tower s (adt)
$M_{\text{stor,size}}^{s}$	Size of tower s (adt)
$Q_{\text{prod,min}}^{Dq}$ $Q_{\text{prod,max}}^{Dq}$	Minimum/maximum production level of heat component Dq for the power plant (MWh/h)
R_{Mcost}^{s}	Penalty cost factor that for surface levels in mass towers (€)
$Rec^{j,s}$	Recipe for connections from mass production to storage and from storage to paper machines
$S_{\text{cons,2bar}}^{j}$	Amount of 2 bar steam consumed by application j (MWh/h)
$S_{\text{cons,3bar}}^{j}$	Amount of 3 bar steam consumed by application j (MWh/h)
$S_{\text{cons,10bar}}^{j}$	Amount of 10 bar steam consumed by application j (MWh/h)
$S_{\text{gen,2bar}}^{j}$	Amount of 2 bar steam consumed by application j (MWh/h)
$S_{\text{pur,max}}$	Maximum purchase of 3 bar steam
$S_{\text{price,3bar}}$	Price of purchased 3 bar steam (€/MWh)
$S_{\text{pur,ch,max}}$	Maximum hourly change of steam purchases (MWh/h)
$S_{\text{pur,3bar}}^{i}$	Amount of steam sold (MWh/h)
$Sch^{j,i}$	Schedule of paper machines (binary)
T_{step}	Timestep of simulation (hour)
w_{price}^{j}	Start-up cost of application j

5.2 Variables

Variables used in this model are listed below.

$\lambda_{\text{CHP}}^{k,i}$	Turbine convex combination weight factor for point k
$CHP^{Dc,i}$	Operating point of the power plant (fuel, electricity, total heat) (MWh/h)
DH_{cooling}^{i}	Amount of additional cooling of DH water (MWh/h)
E_{pur}^{i}	Electricity bought/sold (MWh/h)
F_{cost}^{i}	Cost of consumed fuel (€/h)
$GW_{\text{stonesON}}^{i,l_{GW}}$	Number of stones that are ON
$GW_{\text{active}}^{i,l_{GW}}$	Binary variable denoting that a GW line is ON.
$M_{\text{abschange}}^{s,i}$	Absolute value of $M_{\text{change}}^{s,i}$ (adt)

$M^{s,i}_{\text{change}}$	Absolute change in stored amount of mechanical mass in storage s from previous hour (adt)
$M^{i,s_1\to s_2}_{\text{move}}$	Mechanical mass amount moved from storage s_1 to s_2 (adt/hour)
$M^{s}_{\text{stor,init}}$	Initial storage of mass in storage tower s (adt)
$M^{s,i}_{\text{stor,ready}}$	Amount of mechanical mass that has been in storage for the delay time (adt)
$M^{s,i}_{\text{stor,total}}$	Mechanical mass in storage tower s (adt)
$Q^{Dq,i}_{\text{prod}}$	Production of each heat component in the power plant (low and high pressure steam, DH) (MWh/h)
$R^{s,i}_{\text{M,hourly}}$	A helper variable for the calculation of R_{M} (€)
R_{DH}, R_{M}, R_{S}	Total penalty costs from DH, mass, and steam processes (€)
$S^{i}_{\text{pur,3bar}}$	Amount of purchased 3 bar steam (MWh/h)
$S^{i}_{\text{red,10bar}}$	Amount of 10 bar steam lowered to 3 bar level (MWh/h)
$S^{i}_{\text{red,3bar}}$	Amount of 3 bar steam lowered to 2.5 bar level (MWh/h)
$S^{i}_{\text{vent,2bar}}$	Steam (2 bar) vented into outside air (MWh/h)
$S^{i}_{\text{vent,3bar}}$	Steam (3 bar) vented into outside air (MWh/h)
$S^{i}_{\text{vent,10bar}}$	Steam (10 bar) vented into outside air (MWh/h)
$w^{j,i}$	List of start-ups of each machine j (binary)
$Y^{j,i}$	Application j state ON/OFF (binary)

5.3 Sets

The index variables and corresponding sets are listed here.

Dc, Dc_{set}	Power component of CHP production, set of all components (elec, fuel, heat)
Dq, Dq_{set}	Heat component of CHP production, set of all components (10bar, 3bar, DH)
i, i_1, i_2, T, T_{set}	Current timestep (i_x), highest timestep of calculation, set of timesteps (integer)
j, J	Machine, set of all TMP machines and paper machines
$J_c \subset J$	Set of all paper machines
k, K_{op}	Power plant operating point, set of all points
l_{GW}, L_{GW}	GW line, set of all GW lines
s, s_1, s_2, S	Storage tower (s_x), set of towers

5.4 Objective function

The objective function OBJ is the cost of operation for the paper mill and power plant during the planning period T. The objective function is given by

$$OBJ = \sum_{i=1}^{T} \left\{ \left[E^{i}_{\text{pur}} E^{i}_{\text{price}} + F^{i}_{\text{cost}} + S^{i}_{\text{pur,3bar}} S_{\text{price,3bar}} \right] T_{\text{step}} \right\} + R_{\text{DH}} + R_{\text{S}} + R_{\text{M}}, \tag{1}$$

where E^i_{pur} and E^i_{price} are the amount and price of purchased electricity, respectively, F^i_{cost} is the fuel cost of the plant, $S^i_{\text{pur,3bar}}$ and $S_{\text{price,3bar}}$ are the amount and price of purchased steam, respectively, and T_{step} is the timestep of the calculation. The penalty costs R_{DH}, R_{S}, and R_{M} are related to DH, steam, and mechanical mass processes, respectively.

5.5 Constraints

5.5.1 CHP plant operating point

The relationship is modeled between the power plant's i) electricity production to the mill, ii) total heat production, and iii) total fuel consumption. The plant is modeled as a set of operating points, which are combinations of the mentioned values similar to [27]. The plant can operate in convex combinations of known extremal operating points. The extremal operating points are chosen so that their convex combinations span the most common historical operating points of the power plant. As such, the most typical operation of the power plant is modeled, which implies there are many simplifications, e.g. the amount of boilers in use is not considered. The operating points of the CHP plant are determined by

$$CHP^{Dc,i} = \sum_{k \in K_{\text{op}}} \left(\lambda^{k,i}_{\text{CHP}} K^{k,Dc}_{\text{CHP}} \right) \qquad \forall i \forall Dc, \tag{2}$$

where $CHP^{Dc,i}$ contains the values of the power plant's operating points, and $K^{k,Dc}_{\text{CHP}}$ contains data of the extremal operating points. The variable $CHP^{Dc,i}$ is the convex combination of all extremal operating points K_{op}. The weight factor for each extremal point is contained in $\lambda^{k,i}_{\text{CHP}}$. Additionally, the following two constraints are required:

$$\begin{aligned} \sum_{k \in K_{\text{op}}} \lambda^{k,i}_{\text{CHP}} &= 1 \qquad && \forall i, \\ \lambda^{k,i}_{\text{CHP}} &\geq 0 \qquad && \forall i \forall k. \end{aligned} \tag{3}$$

The above equations are related to the convex combinations method [28]. The fuel consumption of the power plant is estimated from the fuel power by

$$F^i_{\text{cost}} = CHP^{fuel,i} F_{\text{price}} / F_{\text{eff}} \qquad \forall i, \tag{4}$$

where F^i_{cost} is the fuel cost of the power plant, $CHP^{fuel,i}$ is the fuel power use, F_{eff} is the fuel burning efficiency describing the relationship between fuel lower heat value and the gained burning power, and F_{price} is the cost of the average fuel that is used in the power plant.

5.5.2 Steam and district heating

The heat production in the power plant is technically very flexible. In this model, the division of the total heat production into steam and DH has been left free, except for minimum and maximum values for each. These values are determined from historical data. This method of modeling is simplistic in that it does not consider the technical constraints of the power plant. However, this mostly affects the economy of certain combinations of production levels, but not their feasibility. Thus, the flexibility of the power plant is not misinterpreted.

Total heat production of the power plant is given by

$$CHP^{heat,i} = \sum_{Dq \in Dq_{\text{set}}} Q_{\text{prod}}^{Dq,i} \qquad \forall i, \tag{5}$$

where $CHP^{heat,i}$ is the total heat production and $Q_{\text{prod}}^{Dq,i}$ is the production of heat component $Dq \in Dq_{\text{set}}$. Minima and maxima for the heat components are set by

$$Q_{\text{prod,min}}^{Dq} \leq Q_{\text{prod}}^{Dq,i} \leq Q_{\text{prod,max}}^{Dq} \qquad \forall i \forall Dq, \tag{6}$$

where $Q_{\text{prod,min}}^{Dq}$ and $Q_{\text{prod,max}}^{Dq}$ are the minimum and maximum values of each heat component, respectively.

The following three equations define the steam power balances of the paper mill. Note that the condense steam is not considered in these equations. This is because heat recovery is integrated in the mill processes. The condense steam is used in parts of the process that are not modeled in this work. For this reason all calculations are made based on the steam power going into each application.

The power balance of consumed 2.5 bar steam is described by

$$\sum_{j \in J} \left[(S_{\text{gen,2bar}}^{j} - S_{\text{cons,2bar}}^{j}) Y^{j,i} \right] + S_{\text{red,3bar}}^{i} = S_{\text{vent,2bar}}^{i} \qquad \forall i, \tag{7}$$

where $S_{\text{gen,2bar}}^{j}$ and $S_{\text{cons,2bar}}^{j}$ are the generation and consumption of 2.5 bar steam in each machine of the paper mill, and $S_{\text{vent,2bar}}^{i}$ is the power of steam vented out. The variable $Y^{j,i}$ is a binary ON/OFF variable for each application. Steam consumption has only been considered when the machine is on. The balance for 3 bar steam is given by

$$\begin{aligned} Q_{\text{prod}}^{3bar,i} + S_{\text{pur,3bar}}^{i} + S_{\text{red,10bar}}^{i} = \sum_{j \in J} \left(S_{\text{cons,3bar}}^{j} Y^{j,i} \right) \\ + S_{\text{vent,3bar}}^{i} + S_{\text{red,3bar}}^{i} + S_{\text{sold,3bar}}^{i} \qquad \forall i, \end{aligned} \tag{8}$$

where $Q_{\text{prod}}^{3bar,i}$ is the generation power of 3 bar steam in the power plant, $S_{\text{pur,3bar}}^{i}$ is the amount of purchased 3 bar steam, $S_{\text{red,10bar}}^{i}$ is the amount of reduced 10 bar steam, and $S_{\text{sold,3bar}}^{i}$ is the amount of sold steam. The balance equation of 10 bar steam is similar and is presented by

$$Q_{\text{prod}}^{10bar,i} = \sum_{j \in J} \left(S_{\text{cons,10bar}}^{j} Y^{j,i} \right) + S_{\text{vent,10bar}}^{i} + S_{\text{red,10bar}}^{i} \qquad \forall i, \tag{9}$$

where the variables are similar to Equations (7) and (8). The generation of 10 bar steam in the TMP lines is not included in Equation (9), because the steam is consumed in processes that are outside the scope of this model.

Purchasing 3 bar steam from an external company is limited in the model by a maximum amount and change. This is to make it realistic from the point of view of the steam producer. All limits are gathered from historical data. The following equations limit the steam purchases:

$$S^{i}_{\text{pur,3bar}} \leq S_{\text{pur,max}} \qquad \forall i, \tag{10}$$

and

$$-S_{\text{pur,ch,max}} \leq S^{i}_{\text{pur,3bar}} - S^{i+1}_{\text{pur,3bar}} \leq S_{\text{pur,ch,max}} \qquad \forall i \leq T-1. \tag{11}$$

In the above equations $S^{i}_{\text{pur,3bar}}$ is purchased 3 bar steam power and $S_{\text{pur,max}}$ and $S_{\text{pur,ch,max}}$ are the maximum purchased power and maximum hourly change of purchased amount, respectively.

District heating is balanced by equation

$$Q^{DH,i}_{\text{prod}} = DH^{i}_{\text{req}} + DH^{i}_{\text{cooling}} \qquad \forall i, \tag{12}$$

where $Q^{DH,i}_{\text{prod}}$ is DH production of the power plant, DH^{i}_{req} is the DH demand and DH^{i}_{cooling} is the amount of additional cooling of DH water (heat removed from DH water). The exclusion of DH^{i}_{cooling} in the model can be argued, because DH production is only considered because of its effect on power plant operation. It is included here to create an option of overproduction in all heat components. In practice, the heat component that is overproduced depends on assigned costs of steam reduction, steam venting, and DH cooling. Other features of DH production that are left out in this model are the DH accumulator, DH electricity generation and DH generation from low pressure steam, which are described in Section 3.2.1. The modeled DH requirements come from historical data.

The modeled DH additional cooling is not limited by capacity, but it does carry a cost. The DH costs are given by

$$R_{\text{DH}} = \sum_{i=1}^{T} \left(DH_{\text{ccost}} DH^{i}_{\text{cooling}} T_{\text{step}} \right), \tag{13}$$

where DH_{ccost} is the cost of additional cooling. The penalty cost of steam management (R_{S}) is defined in a similar manner, which is left out of this description. The cost is caused by venting out steam and reducing it to a lower pressure level.

5.5.3 Electricity

Electricity production and consumption are balanced with the equation

$$CHP^{elec,i} + E^{i}_{\text{pur}} = \sum_{j \in J} \left(E^{j}_{\text{cons}} Y^{j,i} \right) \qquad \forall i, \tag{14}$$

where $CHP^{elec,i}$ is the electricity production and E^{j}_{cons} is the electricity consumption of each machine j.

5.5.4 Mechanical mass

Mechanical mass production is balanced in the next equations. Total mass storage in each storage tower can be calculated by

$$\begin{aligned} M_{\text{stor,total}}^{s_1,i_1} = M_{\text{stor,init}}^{s_1} + \sum_{i_2=1}^{i_1} \Bigg\{ & \sum_{j \in J} \left[(M_{\text{prod}}^{j} - M_{\text{cons}}^{j}) Rec^{j,s_1} Y^{j,i_2} T_{\text{step}} \right] \\ & + \sum_{s_2 \in S} \left[M_{\text{move}}^{i_2,s_2 \to s_1} - M_{\text{move}}^{i_2,s_1 \to s_2} \right] T_{\text{step}} \Bigg\} \qquad \forall s_1 \forall i_1, \end{aligned} \tag{15}$$

where $s_1, s_2 \in S$ and $0 \leq i_1, i_2 \leq T$, $M_{\text{stor,init}}^{s_1}$ is the initial stored amount of mechanical mass, M_{prod}^{j} and M_{cons}^{j} are mass productions and consumptions of machines j, Rec^{j,s_1} contains a matrix which sets the recipe by which mass is moved from tower to tower, T_{step} is the timestep of the calculation (typically 1 hour), and $M_{\text{move}}^{i_2,s_2 \to s_1}$ and $M_{\text{move}}^{i_2,s_1 \to s_2}$ are the amounts of mass moved between towers s_1 and s_2 (adt/hour).

Some processes in towers take more time than one timestep. In this situation the Equation (15) would allow the model to unrealistically move forward mass that is not yet processed. The amount of mechanical mass that is ready to be moved is calculated by the equation

$$\begin{aligned} M_{\text{stor,ready}}^{s_1,i_1} = M_{\text{stor,init}}^{s_1} + \sum_{i_2=1}^{i_1 - M_{delay}^{s_1}} & \Bigg\{ \sum_{j \in J} \left[(M_{\text{prod}}^{j} - M_{\text{cons}}^{j}) Rec^{j,s_1} Y^{j,i_2} \right] \\ & + \sum_{s_2 \in S} \left(M_{\text{move}}^{i_2,s_2 \to s_1} - M_{\text{move}}^{i_2,s_1 \to s_2} \right) \Bigg\} T_{\text{step}} \\ & - \sum_{i_2 = i_1 - M_{\text{delay}}^{s_1}}^{i_1} \Bigg\{ \sum_{j \in J} \left[M_{\text{cons}}^{j} Rec^{j,s_1} Y^{j,i_2} \right] \\ & + \sum_{s_2 \in S} M_{\text{move}}^{i_2,s_1 \to s_2} \Bigg\} T_{\text{step}} \qquad \forall s_1 \forall i_1, \end{aligned} \tag{16}$$

where all parameters and variables have been described after Equation 15. Equation (16) is used to calculate the amount of mass in each tower that has already been there for the duration of the processing. It should be noted that the towers are filled from the top and emptied from the bottom. For this reason, ready mass can be removed at will. The processing time in a tower is given as an integer amount of time steps the process takes.

Next, the thought process behind Equation (16) will be clarified. The summation of the ready mass is done in two parts. First, the amount of storage is calculated for mass that has been brought into the storage tower so long ago, it is not affected by the delay anymore (current timestep minus delay steps). Then, that mass is reduced which has been taken out during the current delay time. This results to the amount of mass that has been in the storage long enough to be used, but has not yet been removed from the storage tower. The mass storage amounts described in Equations (15) and (16) are restricted by the following equations:

$$M^{s}_{\text{stor,min}} \leq M^{s,i}_{\text{stor,total}} \leq M^{s}_{\text{stor,max}} \qquad \forall s \forall i, \tag{17}$$

and

$$M^{s,i}_{\text{stor,ready}} \geq 0 \qquad \forall s \forall i. \tag{18}$$

In the above equations, $M^{s}_{\text{stor,min}}$ and $M^{s}_{\text{stor,max}}$ are the minimum and maximum allowed amounts of mechanical mass storage, respectively, in each storage tower s.

Moving mass between storages is represented by the equation

$$M^{i,s_1 \to s_2}_{\text{move}} = M^{s_1,s_2}_{\text{rec}} \sum_{s_3 \in S} M^{i,s_3 \to s_2}_{\text{move}} \qquad \forall s_1, s_2 \forall i, \tag{19}$$

where the parameter M^{s_1,s_2}_{rec} defines what fraction of mass that is moved to s_2 must come from s_1. The summation term yields the total mass moved to s_2. In other words, the equation forces all mass moves from storage to storage be such that the recipe M^{s_1,s_2}_{rec} is satisfied. Index s_3 belongs to set of storage towers, S.

If no constraints are set for the final storage of a tower after the modeling period, it is naturally optimal to use up all stored mass. This is limited by

$$M^{s,T}_{\text{stor,total}} / M^{s}_{\text{stor,size}} \geq M^{s}_{\text{end}} \qquad \forall s, \tag{20}$$

where M^{s}_{end} is the required storage surface level for each tower at the end of the modeling period, and $M^{s}_{\text{stor,size}}$ is the size of the tower. With multiple storage towers it is not trivial to decide how mechanical mass is stored and moved from storage to storage. A small penalty cost is added to encourage realistic operation of storage towers. This is described next. The storage change is defined by

$$\begin{aligned} M^{s,1}_{\text{change}} &= M^{s,1}_{\text{stor,total}} - M^{s}_{\text{stor,init}} && \forall s, \\ M^{s,i}_{\text{change}} &= M^{s,i}_{\text{stor,total}} - M^{s,i-1}_{\text{stor,total}} && \forall s, i \geq 2, \end{aligned} \tag{21}$$

where $M^{s,i}_{\text{change}}$ is the change in stored amount in each storage tower. It is constrained by equations

$$\begin{aligned} M^{s,i}_{\text{abschange}} &\geq M^{s,i}_{\text{change}} && \forall s \forall i, \\ M^{s,i}_{\text{abschange}} &\geq -M^{s,i}_{\text{change}} && \forall s \forall i. \end{aligned} \tag{22}$$

where $M^{s,i}_{\text{abschange}}$ is, at minimum, the absolute value of $M^{s,i}_{\text{change}}$. The value of $M^{s,i}_{\text{abschange}}$ is guided by a penalty cost defined in equations

$$\begin{aligned} R^{s,i}_{\text{M,hourly}} &\geq R^{s}_{M,cost}(M^{s,i}_{\text{abschange}} - M^{s}_{\text{changerate}}) && \forall s \forall i, \\ R^{s,i}_{\text{M,hourly}} &\geq 0 && \forall s \forall i, \end{aligned} \tag{23}$$

where $R^{s,i}_{\text{M,hourly}}$ is the penalty cost for each storage and hour, and $R^{s}_{M,cost}$ is a cost factor defined for each tower separately. This formulation relies on the minimization algorithm to maintain such rates of change $M^{s,i}_{\text{abschange}}$ that are close to the parameter $M^{s}_{\text{changerate}}$. The total penalty cost of mass processing is finally calculated by

$$R_M = \sum_{s \in S} \sum_{i=1}^{T} R^{s,i}_{\text{M,hourly}} + \sum_{j \in J} w^{j,i} w^{j}_{\text{price}}, \tag{24}$$

where R_M is the total penalty cost of mass processing, $w^{j,i}$ is a binary variable containing the startups (see Section 5.5.5), and w^{j}_{price} is the start-up cost. Independently from the start-up cost, Equations (21)–(24) constitute a formulation of maximum change rate for each storage tower, where bypassing the maximum rate causes a cost. This makes it possible to prioritize the stability of the surface level of selected towers.

There is a limit for how many grinding stones must be ON for a GW line to be running. The limitation is set by the design of the processing line and is implemented by the following equations:

$$GW^{i,l_{GW}}_{\text{stonesON}} - GW^{i,l_{GW}}_{\text{active}} A_{\text{GW}} \leq 0 \qquad \forall i \forall l_{GW} \tag{25}$$

and

$$GW^{i,l_{GW}}_{\text{stonesON}} + (1 - GW^{i,l_{GW}}_{\text{active}}) A_{\text{GW}} \geq GW^{l_{GW}}_{\text{stones,min}} \qquad \forall i \forall l_{GW}. \tag{26}$$

Here, $GW^{i,l_{GW}}_{\text{stonesON}}$ is the amount of stones in the ON state, $GW^{i,l_{GW}}_{\text{active}}$ is a free binary variable, A_{GW} is a sufficiently large positive integer, $GW^{l_{GW}}_{\text{stones,min}}$ is the required minimum amount of stones ON, and l_{GW} is an index variable denoting a GW line. Equations (25) and (26) constitute a linearized condition according to which either zero or at least $GW^{l_{GW}}_{\text{stones,min}}$ grinding stones must be on.

5.5.5 Other constraints

The list of start-ups of machines is described by the following equations:

$$\begin{aligned} w^{j,i} &\geq Y^{j,i} - Y^{j,i-1} && \forall i \forall j, \\ w^{j,i} &\geq 0 && \forall i \forall j. \end{aligned} \tag{27}$$

Finally, schedules of paper machines are forced to match planning by equation

$$Sch^{j,i} = Y^{j,i} \qquad \forall i, \forall j \in J_c, \tag{28}$$

where $Sch^{j,i}$ is a binary matrix containing the schedule of paper machines $j \in J_c$.

There are additional constraints on the values of some variables. Variables and parameters that are constrained to binary or integer values, or to a certain range, have been noted in the listings in Sections 5.1 and 5.2. Below, variables are listed that are specifically constrained to nonnegative values.

Mass balance: $M_{\text{abschange}}^{s,i}$ $M_{\text{move}}^{i,s_1\to s_2}$ $M_{\text{stor,init}}^{s}$ $M_{\text{stor,ready}}^{s,i}$ $M_{\text{stor,total}}^{s,i}$

Steam balance: $S_{\text{pur,3bar}}^{i}$ $S_{\text{red,10bar}}^{i}$ $S_{\text{red,3bar}}^{i}$ $S_{\text{vent,2bar}}^{i}$ $S_{\text{vent,3bar}}^{i}$ $S_{\text{vent,10bar}}^{i}$

Penalty costs: $R_{\text{M,hourly}}^{s,i}$ R_{DH} R_{S}

Other: $\lambda_{\text{CHP}}^{k,i}$ DH_{cooling}^{i} $Q_{\text{prod}}^{Dq,i}$

5.6 Model statistics

A representative instance of the model has 6567 constraints, and 5284 decision variables, 1008 of which are binary variables.

Solving the model, written with AIMMS 4.5 and solved with CPLEX 12.6.1, takes on average 4 seconds on a normal laptop. However, as is typical with MILP problems, some instances take noticeably longer to solve. Thus, an optimality gap of 0.1 % is used when a series of multiple solves is executed, along with a time limit of 30 seconds.

6 Calculation of regulating costs

6.1 Process description

In the previous section, a MILP model of the operation of the paper mill site was described. In this section, the model is used for studying the ability of the mill site to operate on the regulating power market. More specifically, a process is created for calculating the price of regulation for the mill site from the model results. The model is also modified for this purpose. The process of calculating the costs of regulation can be divided into four steps. These steps are described next. They are also briefly described in Table 1, and illustrated in Figure 3.

Table 1. The process of calculating the costs of executing regulating power bids.

Step	Purpose	Price used	Methods
1	Initial scheduling	Spot forecast	MILP model (as described in Section 5) is solved.
2	Real cost of operation	Spot	New solve with all decision variables locked. Costs will change due to different price profile.
3	Forced regulating schedule	Spot, intra-day	Purchased electricity is forced to change during the first hour(s) of a 24 hour period. Power plant production is locked during that time. After the regulating hours the power plant schedule can be altered, and additional electricity can be purchased from the intra-day market.
4	Calculate cost of regulating	Spot, intra-day	Calculate the difference of total costs in Steps 3 and 2, and divide by amount of regulating power. The result is a cost for regulating.

Step 1

The original MILP model is solved with the forecast spot price of electricity.

Step 2

The exact production plan created in Step 1 is kept, but the price of electricity is changed to the realized spot price of electricity. This gives the realized costs of operation, when the operation has been planned according to a forecast.

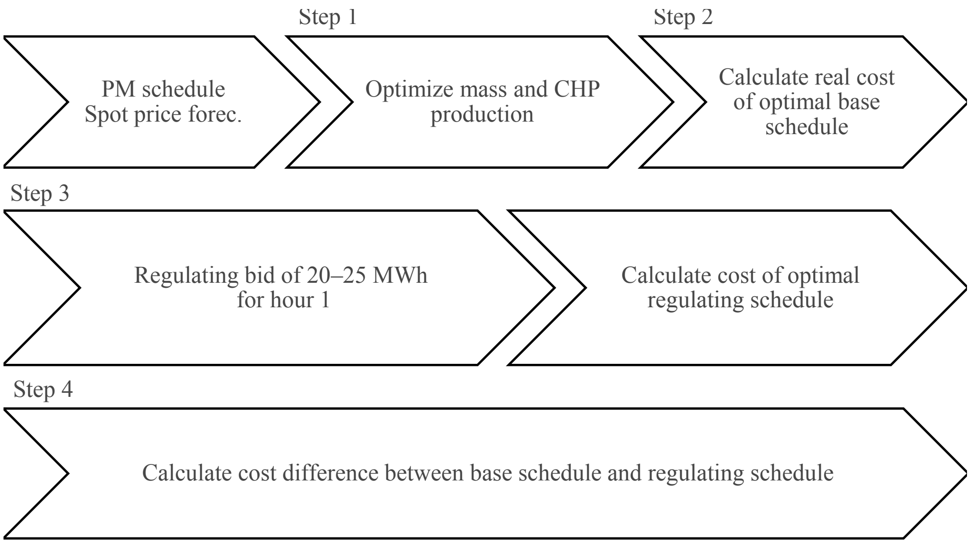

Figure 3. A visualization of the calculation of regulating costs.

Step 3

A production plan is made for an assumed accepted regulating power bid. It is assumed that a regulating bid is made on the first one or several hours of the modeling period. The bid is made for either an increase (down-regulation) or decrease (up-regulation) in electricity consumption, and electricity production can not be affected during the regulating hours. Power plant production and the mechanical mass production schedule is then re-planned so that the results fulfill both the accepted regulating power bid and all original requirements. The purpose of this production plan is to calculate the total costs of executing the regulating power bid without affecting any of the other requirements of operation.

The adjustment in consumption required to fulfill the accepted bid is limited by parameters, but the exact size of it is decided by the model. The model will choose the adjustment that results in the lowest total costs during the modeling period. The purpose of this is to allow the model to freely combine the increase or decrease in electricity consumption from different mechanical mass production machines, as the total sum is not exactly defined.

After regulation, the modeled mill site will have either surplus or deficit of mechanical mass production. The end requirement for stored mechanical mass is the same as originally, which means that in case of up-regulation, the model needs to schedule additional production for hours after the regulating hours. In case of down-regulation this is not necessary as upper limits for mechanical mass production have not been set. However, extra production is not economically optimal. For correcting the surplus or deficit of mechanical mass, the site is allowed to buy or sell additional electricity from or to the intra-day market. It is assumed in this model that this price is always less favourable for the site than spot price would have been. This is a conservative assumption that is explained in more detail in Section 6.3. The amount of traded intra-day electricity is limited to i) the direction that is needed for correcting the mass deficit/surplus, and ii) the same total amount as was traded as regulating power. This prevents speculative trading that is untypical for a paper mill site, and not the main focus of this work. In addition to purchasing electricity, the mill site may also change the production plan of the power plant. These changes can be made to any direction, but not during the regulating hours. This is because regulating can be made by changes in either production or consumption, but not a combination of the two.

Step 4

Step 4 consists of the calculation of additional costs caused by the modeled regulating power bid. The difference between the total costs of the model in Steps 2 and 3 is calculated, and divided by the size of the regulating power bid. This results to the cost of regulating for the modeled bid as €/MWh. It should be noted that this cost does not consider any compensation from the regulating power bid. As it only considers costs caused by the regulation, the cost can be understood as the smallest price of regulation that would have made the bid economically viable.

6.2 Alterations to the model

In this section, the model described in Section 5 is altered to make calculations about the cost of flexibility. Calculation steps described in Section 6 and briefly described in Table 1, are also referred to in this section for clarity. The alterations made in this section relate to step 3, but also affect the equations of steps 1 and 2. The results of steps 1 and 2 are not affected by these changes. Alterations are implemented so that they can effectively be applied or removed by dedicated binary parameter values and applied by using the model with additional constraints.

6.2.1 Parameters

The following parameters are added to the MILP model as part of the alterations in this section:

Reg_{start}	First timestep of regulating (model designed for $Reg_{\text{start}} = 1$)
Reg_{end}	Last timestep of regulating
$E^i_{\text{price,forec}}$	The forecast spot price of electricity (€/MWh)
$E^i_{\text{price,real}}$	The realized spot price of electricity (€/MWh)
$E_{\text{pur,noreg}}$	Electricity purchases in Steps 1 and 2 (MWh)
$E^i_{\text{profit,id}}$	Income or cost from intra-day trading of electricity (€/h)

Reg_{scen}	binary parameter, 1 on the Step 3, 0 otherwise
Reg_{dir}	binary parameter, 1 for up-regulation (decrease consumption), -1 for down-regulation
Reg_{a}^{idT}	Parameter for estimating the price of intra-day electricity
Reg_{b}^{idT}	Parameter for estimating the price of intra-day electricity (€/MWh)
$Reg_{\text{abs,min}}$	Minimum size of the regulating power bid (MWh/h)
$Reg_{\text{lim}+}$	Maximum size of an up-regulating bid (MWh/h)
$Reg_{\text{lim}-}$	Maximum size of a down-regulating bid (MWh/h)

6.2.2 Variables

These variables are added to the model.

$E^i_{\text{price,id}}$	Intra-day price of electricity (€/MWh)
$E_{\text{sold,reg}}$	Constant amount with which electricity purchases are changed from initial to regulating scenario solve, during regulating hours (MWh/h)
$E^i_{\text{pur,id}}$	Amount of trading in the intra-day market (integer) (MWh/h)
OBJ^i_{spot}	Costs from the spot trade (€/h)

6.2.3 Sets

These index variables and corresponding sets are added to the MILP model as part of the alterations in this section.

$Reg_{\text{hrs}} \subset T_{set}$	Set of timesteps for which regulating power is offered
idT, idT_{set}	Term, and a helper set for intra-day price calculation

6.2.4 Constraints

In this section, constraints are discussed which have been added or modified from the original MILP model. The set of regulating hours is defined by

$$Reg_{\text{hrs}} = \{i \in T_{set} | Reg_{\text{start}} \leq i \leq Reg_{\text{end}}\}, \tag{29}$$

where Reg_{hrs} is the set of regulating hours, Reg_{start} is the first, and Reg_{end} is the last timestep (hour) of regulation. The constraints implementing the change the electricity purchases on these hours are presented next. The decrease in electricity purchases is given by

$$E^i_{\text{pur}} = E^i_{\text{pur,noreg}} - E_{\text{sold,reg}} \qquad i \in Reg_{\text{hrs}}, \tag{30}$$

where E^i_{pur} is the purchased electricity during the solve, and $E^i_{\text{pur,noreg}}$ is the electricity purchased in Steps 1 and 2, and $E_{\text{sold,reg}}$ is the time-invariant amount of sold regulating power, which is a variable. The value of $E_{\text{sold,reg}}$ is limited by

$$E_{\text{sold,reg}} Reg_{\text{dir}} \geq Reg_{\text{abs,min}}, \tag{31}$$

where Reg_{dir} denotes the direction of regulation with values 1 and -1 for up- and down-regulation, respectively. The minimum allowed amount of regulation in any direction is denoted by $Reg_{\text{abs,min}}$. The variable $E_{\text{sold,reg}}$ is also limited by

$$Reg_{\text{lim}-} \leq E_{\text{sold,reg}} \leq Reg_{\text{lim}+}, \tag{32}$$

where $Reg_{\text{lim}-}$ and $Reg_{\text{lim}+}$ are limits for the amount of regulating. This prevents the model from implementing unrealistically high regulating power bids.

The model is only allowed to trade on the intra-day market in order to compensate for surplus or deficit in produced mass due to the regulation. The direction of trading is limited by

$$Reg_{\text{dir}} E^i_{\text{pur}} \geq E^i_{\text{pur,noreg}} Reg_{\text{dir}} \qquad i \notin Reg_{\text{hrs}}. \tag{33}$$

The above equation can be understood as two different equations for up-regulation and down-regulation scenarios. These equations are presented next in order to showcase the methodology and make the more complicated equations more accessible. Equation 33 can be broken down to

$$E^i_{\text{pur}} \geq E^i_{\text{pur,noreg}} \qquad i \notin Reg_{\text{hrs}}, Reg_{\text{dir}} = 1, \tag{34}$$

and

$$E^i_{\text{pur}} \leq E^i_{\text{pur,noreg}} \qquad i \notin Reg_{\text{hrs}}, Reg_{\text{dir}} = -1. \tag{35}$$

These two equations are representations of Equation (33), and they are not part of the model. The variable E^i_{pur} contains both the original spot traded amount and the intra-day traded amounts. For example in case of up-regulation, there is a deficit of mass production during the regulating hours. For this reason additional production must be done later during the modeling period. The model needs to be able to increase electricity purchases for these hours. The ability to sell electricity in the intra-day market, however, is not needed. The opposite is true for down-regulation scenarios.

The amount of intra-day trading is limited to the amount of sold regulating power. This is implemented by

$$Reg_{\text{dir}} \sum_{i=1}^{T} E^i_{\text{pur,id}} \leq E_{\text{sold,reg}} Reg_{\text{dir}}, \tag{36}$$

where $E^i_{\text{pur,id}}$ is the amount of electricity purchased in the intra-day market. It is defined by the following equations:

$$\begin{aligned} E^i_{\text{pur,id}} &= 0 && \forall i \in Reg_{\text{hrs}}, \\ E^i_{\text{pur,id}} &= E^i_{\text{pur}} - E^i_{\text{pur,noreg}} && \forall i \notin Reg_{\text{hrs}}. \end{aligned} \tag{37}$$

The variable $E^i_{\text{pur,id}}$ can only hold integer values, i.e. intra-day purchases and sales are integer-sized. Due to this, and the strict electricity balance, some involvement from the power plant is necessary in the majority of intra-day purchases.

The cost of spot electricity in Step 3 is equal to that of Step 2. This is described by

$$OBJ^i_{\text{spot}} \geq E^i_{\text{pur,noreg}} E^i_{\text{price}} \qquad \forall i, \tag{38}$$

where OBJ^i_{spot} is one summation term of the objective function (1), and E^i_{price} is the price of electricity used in the scenario, which in Steps 2 and 3 is the realized spot price $E^i_{\text{price,real}}$, and in Step 1 the spot price forecast $E^i_{\text{price,forec}}$. The MILP model will set the value of OBJ^i_{spot} as low as possible. Equation (38) is only meaningful in step 3 because of the values of $E^i_{\text{pur,noreg}}$. In Steps 1 and 2 the spot trading cost is set by

$$OBJ^i_{\text{spot}}(1 - Reg_{\text{scen}}) \geq E^i_{\text{pur}} E^i_{\text{price}}(1 - Reg_{\text{scen}}) \qquad \forall i, \tag{39}$$

where Reg_{scen} is a binary parameter with the value 1 if the current scenario is a regulating scenario (Step 3), and 0 otherwise. During the regulating scenario the constraint of Equation (39) is always satisfied. The cost or income from intra-day power trading is calculated by

$$E^i_{\text{profit,id}} = -E^i_{\text{pur,id}} Reg_{\text{scen}} E^i_{\text{price,id}} \qquad \forall i \notin Reg_{\text{hrs}}, \tag{40}$$

where $E^i_{\text{profit,id}}$ is the profit (or cost) from intra-day trading, and $E^i_{\text{price,id}}$ is the price of intra-day electricity. The latter is estimated by the equation

$$E^i_{\text{price,id}} = Reg^{idT}_{\text{a}} E^i_{\text{price,real}} + Reg^{idT}_{\text{b}} \qquad \forall i, \tag{41}$$

where Reg^{idT}_{a} and Reg^{idT}_{b} are parameters used to estimate the price of intra-day electricity. Equation (41) is discussed in detail in Section 6.3.

6.2.5 Objective function

The objective function OBJ_{alt} for the altered MILP model is

$$\begin{aligned} OBJ_{\text{alt}} = \sum_{i=1}^{T} \left(OBJ^i_{\text{spot}} - E^i_{\text{profit,id}} + S^i_{\text{pur,3bar}} S_{\text{price,3bar}} + F^i_{\text{cost}} \right) T_{\text{step}} \\ + R_{\text{DH}} + R_{\text{S}} + R_{\text{M}}, \end{aligned} \tag{42}$$

where the terms are almost identical to the ones in the objective function of the original MILP model (see Equation (1)). The only difference is that the amount and price of electricity ($E^i_{\text{pur}} E^i_{\text{price,pur}}$ in the original formulation) has here been reformatted into the form $OBJ^i_{\text{spot}} - E^i_{\text{profit,id}}$, which considers the intra-day trading described in this section.

6.3 Estimation of the intra-day price

In this work, the price of intra-day electricity is estimated from the hourly realized spot price. This is an estimation from a representative sample of intra-day price data provided by the case company [29]. A plot of this sample is shown in Figure 4. It is seen that there is a strong correlation between the intra-day and spot price of electricity, especially in the range of 20–50 €/MWh of spot prices. Similar figures can be drawn for data where only down-regulation hours are considered, or only up-regulation hours. A linear trendline can be drawn for each respective case. For all hours the equation of the trendline is

$$E_{\text{price,id}} = 0.94E_{\text{price,real}} + 2.05, \tag{43}$$

for the data of down-regulation hours only the equation of the trendline is

$$E_{\text{price,id}} = 0.93E_{\text{price,real}} + 0.34, \tag{44}$$

and for the data of up-regulation hours the corresponding equation is

$$E_{\text{price,id}} = 1.04E_{\text{price,real}} + 1.45. \tag{45}$$

From these equations it is visible that during down-regulation hours, the Elbas price is typically lower than the Elspot price, and during up-regulation hours it is typically higher. The price of intra-day electricity is estimated by these equations in this work.

In the model, the regulation direction is only known for the regulating hours. The direction of regulation typically remains the same for only 2–3 hours at a time [29]. However, the model may do intra-day trading at most 23 hours later. Thus, it is not known what the direction of regulation will be at that time. In order to make a conservative estimate, it is assumed that the direction of regulation remains the same for the duration of the modeling period. This makes the estimated intra-day price always unfavorable with respect to the realized spot price. This works in preventing the model from gaining too much benefit from the ability to trade on the intra-day market in Step 3, as this trading is not done in Step 2 either.

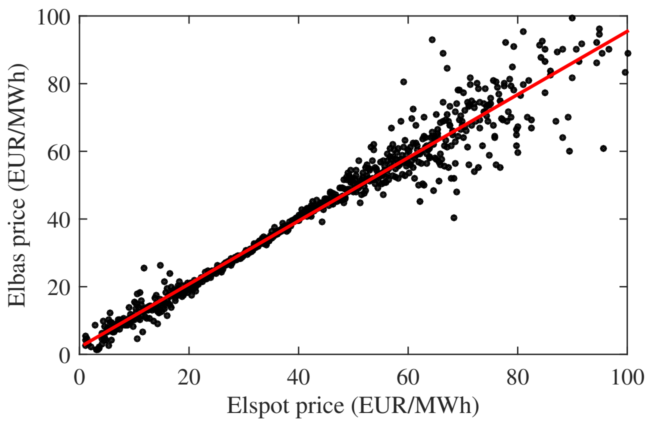

Figure 4. A representative sample of Elspot and Elbas prices provided by the case company [29]. A linear fit is shown for the data points.

7 Results

In Section 5, a model was presented that makes optimal mechanical mass production schedules and energy management strategies for the case site. In Section 6, the model was extended and a process was introduced that allows the cost analysis of accepted regulating power bids. In this section, the results of two use cases of the model are presented. In Case 1, an optimized production plan is created for mechanical mass production and the power plant. The features of the model are discussed. A regulating scenario is also modeled, where the previously mentioned production plan is modified to provide regulating power to the electricity market. In Case 2, the regulating scenario of another 24 hour period is studied. The optimality of the mechanical mass production schedule of the regulating scenario is challenged with another, manually chosen schedule. The causes of cost differences between the schedules are analyzed. In addition to the two use cases, the model is run through hundreds of regulating scenarios, and the results are discussed.

The parameters in this section have been modified from real data of the case mill site, and the results have been calculated with these modified parameters. The results and parameters show the same characteristics as the real data.

7.1 Case 1: Optimal scheduling and a regulating scenario

7.1.1 Base scenario

The purpose of this section is to examine the optimal schedule of mechanical mass production created by the model during one 24 hour period. The chosen period is on a weekday in January 2014, starting at 3 a.m. The forecast and realized prices of electricity are presented in Figure 5. The large scale shapes and price levels of the curves are similar to each other. The optimal schedule from solving the model with the price forecast is presented in Figure 6. All paper machines are set to be ON during the modeling period, except for PM4, which is OFF during hours 6–13.

The results of the model in this base scenario will be analyzed next. All GW and TMP lines operate at full during hours 1–4. This is because the price of electricity is low, and all machines are assumed to be ON during hour 0, which means there are no start-up costs. After this, GW2 slowly decreases production to four stones. Four grinding stones is the minimum allowed amount for GW2. GW1 lowers production from all six stones to only four after hour 8. It continues with four stones, while the minimum amount of grinding stones is three for GW1. The grinding stones are run by electric motors in pairs. Stones connected to the same motor have equal calculated electricity consumptions. A small constant has been added to the consumption of one stone of each pair to ensure a consistent running order in the model. Due to the almost equal consumptions of electricity, it is typical for the model to run either both or none of the stones, instead of a single stone. This does not of course always happen, as is seen from the schedule of GW2 on hour 5.

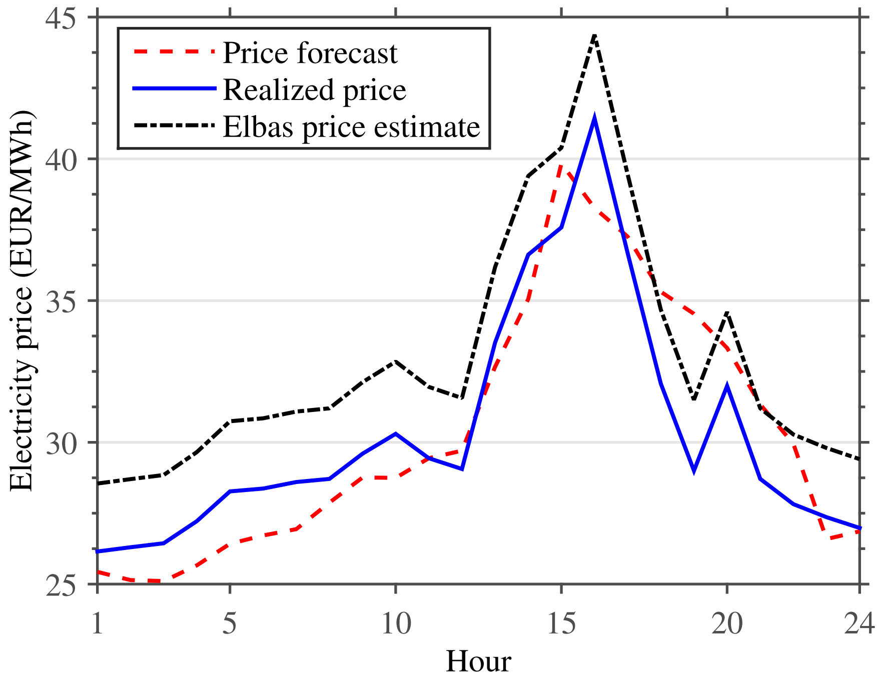

Figure 5. Prices of electricity in Case 1.

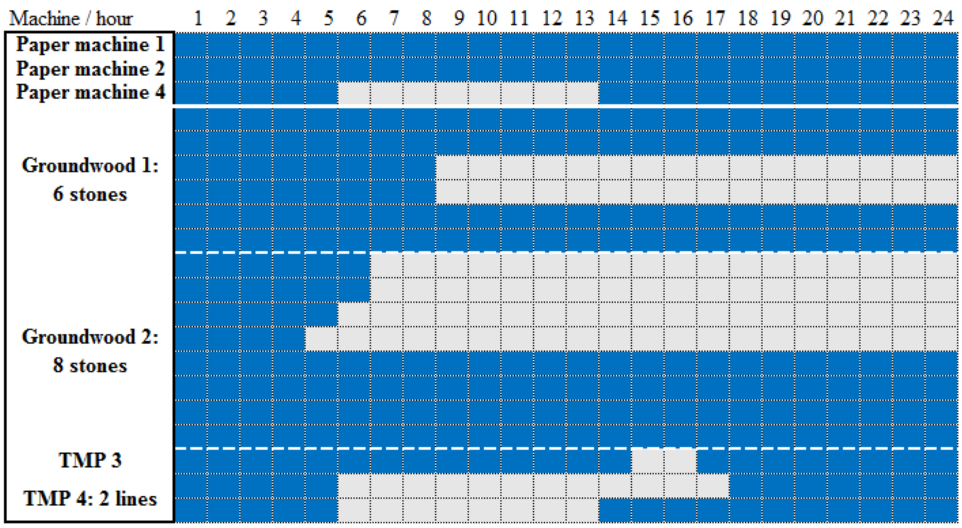

Figure 6. Optimal production schedule for mechanical mass production. The blue blocks indicate that the machine of the corresponding line was ON during the hour of the column. The grey blocks indicate that the machine was OFF during that hour.

Due to the production requirement of TMP3, the line can only stop for two hours during the modeling period. According to Figure 6, this is done for hours 15–16, the forecast price peak hours. TMP3 and both TMP4 lines produce 2.5 bar steam to be used in the paper machines PM2 and PM4. During hours 6–13, when PM4 is OFF, TMP4 is halted completely. It is important to note that these are not the hours of the highest price of electricity (like for TMP3), but for the lowest need of steam. If the TMP4 lines were ON, extra steam would be vented out. The TMP3 line alone is enough to cover almost all of the need of 2.5 bar steam during hours 6–13. The rest of the steam is reduced from 3 bar steam. One of the TMP4 lines is OFF also during the highest forecast prices.

The modeled network of mass storage and processing towers is shown in Figure 7. An hourly graph of the surface level (fill level) of each storage tower is shown. Total production with respect to maximum production is also shown for each type of production. Towers TMP3 latency, TMP4 latency and TMP4 bleaching are processing towers, where the stability of the surface level maintained. The surface levels of storage towers of usable mass S1, S2, S4, and S5 vary notably as expected.

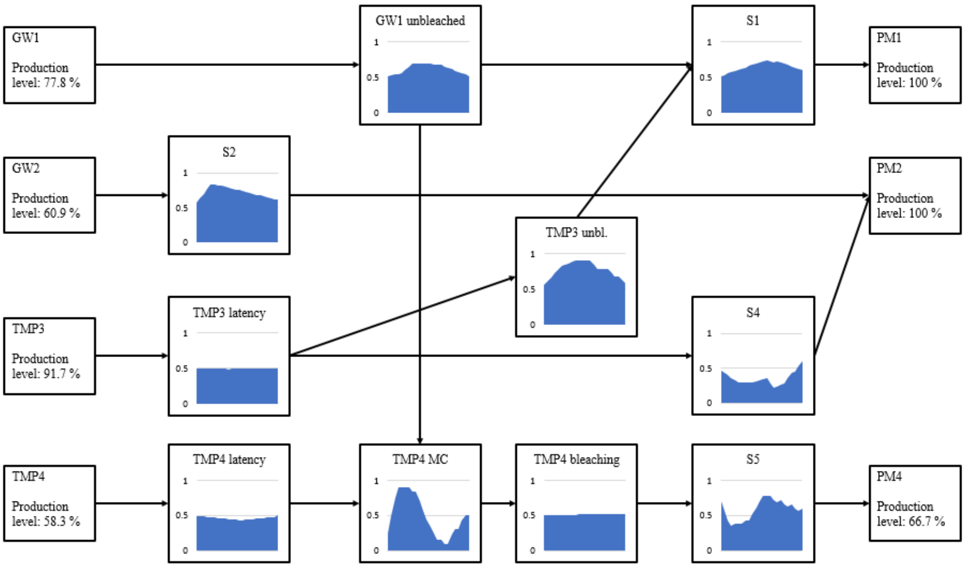

Figure 7. Illustration of the surface levels of the storage and processing towers of mechanical mass during the base scenario of Case 1.

Power plant operation during the modeling period is visualized in Figure 8. The power plant can operate in any point defined by the convex hull surrounding the extremal operating points. This area is called the operating region of the power plant. By comparing the operating points used by the model with the operating region, it is seen that the electricity production of the plant is very low on average with respect to its production capacity. Operating points between only two extremal operating points are used during most hours. In the operating points used by the model that are not on the aforementioned line, it is seen that for any given heat production, a near maximum amount of electricity is produced. These notions reflect the relationship between the price of fuel, the purchase price of steam, and the price of electricity.

The division of heat into DH and low and middle pressure steams is shown in Figure 9. As the modeled period is during the winter, DH production is dominant. Second highest is the production of low pressure steam, and finally only a small portion of heat energy is used toward middle pressure steam production. The highest production

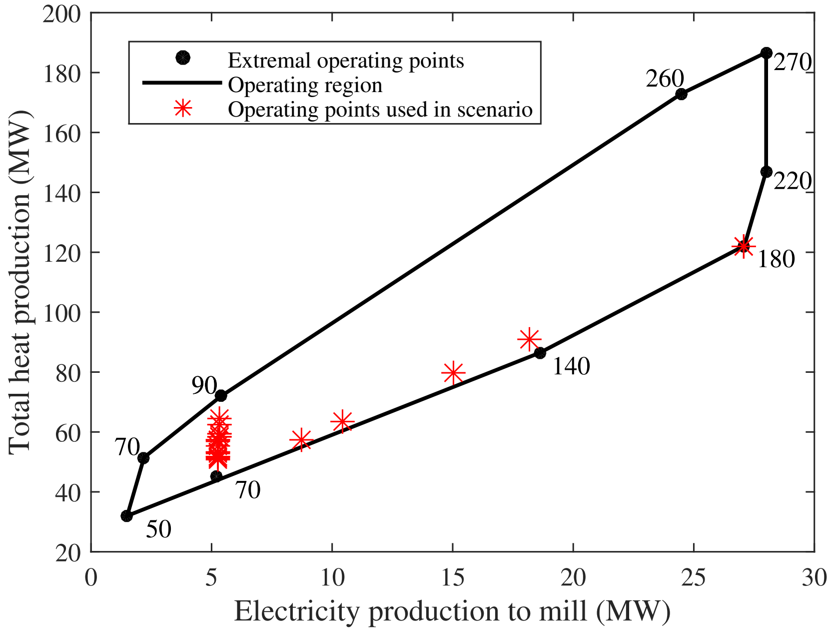

Figure 8. Power plant operation during the modeling period. The convex hull enclosing the extremal operating points denotes the operating region of the plant. The Fuel power of each extremal operating point is marked in the figure with a number (MW).

of heat is on the price peak hours 15–16. Most increase from previous hours comes from 3 bar steam production. This steam is used to i) compensate for the TMP3 steam production that ends after hour 14, ii) feed steam to PM4, which starts after hour 13 and iii) decrease the amount of purchased steam from the amounts of the previous hours. The last notion reflects that the change in electricity production is not only a question of price of electricity, but also of the price of purchased steam.

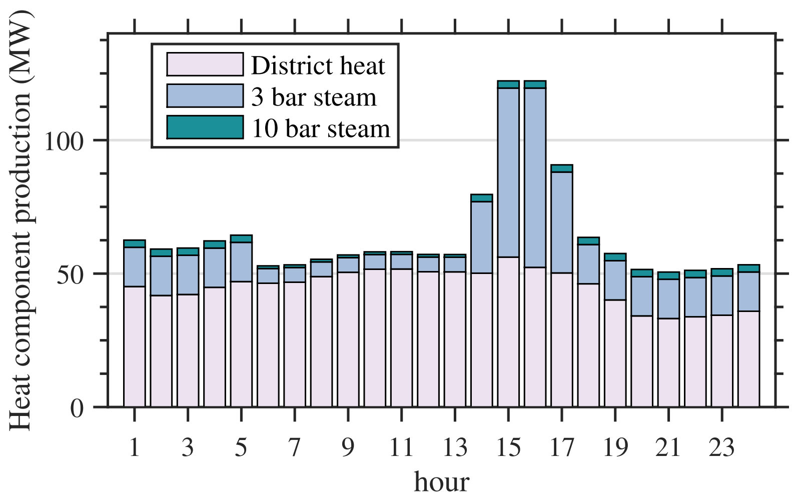

Figure 9. Power plant heat production for each heat component.

The electricity procurement of the mill site is shown in Figure 10. It is seen that the total consumption of electricity is clearly the highest at the beginning of the day, and high again at the end of the day. Most of the electricity consumption is by paper machines, followed by TMP3 and then TMP4 lines. The line plot in Figure 10 is the realized price curve, while scheduling was done by the price forecast, where the peak hour was one hour earlier. The electricity production of the power plant increases during the price peak hours. For a CHP plant increased production of electricity also means an increased production of heat. This increase can be seen in Figure 9.

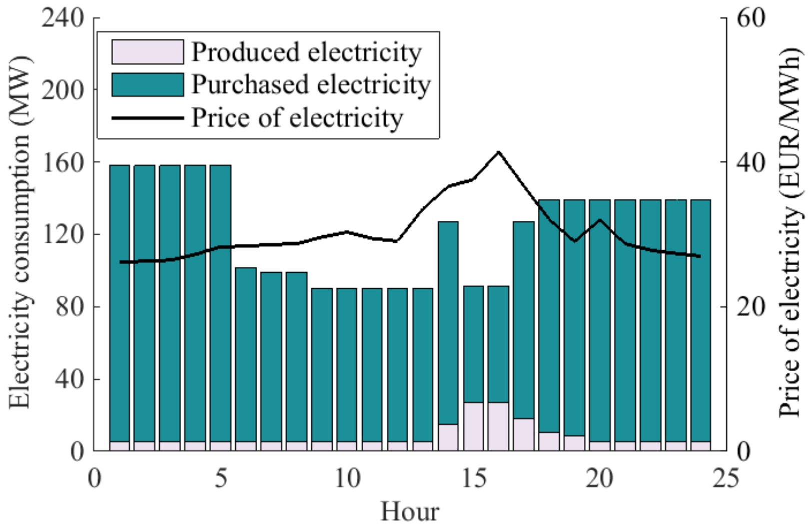

Figure 10. The electricity procurement of the paper mill site.

7.1.2 Regulating scenario

The regulating scenario illustrates up-regulation where the model is forced to decrease the electricity consumption of mechanical mass production compared to the original scenario. The decrease in this case is 20–25 MWh during the first hour of the modeling period. The realized decrease is 20 MWh. This electricity is sold as regulating power to the grid. No compensation is however gained by the model for this electricity, but rather this scenario is used to calculate what the price of the regulating power should at minimum be for the sale to be profitable. The resulting mechanical mass production schedule is shown in Figure 11. This is the schedule that results in the lowest total cost of operation considering the regulation of the specified size range.

The model has chosen to turn OFF GW lines. The lines to turn OFF have been chosen so that only the minimum amount of grinding stones is left ON during hour 1. Typically the lines that are turned OFF are the same lines that are OFF later during the modeling period. This reflects that the model usually shuts down the stones with the least production per electricity consumption.

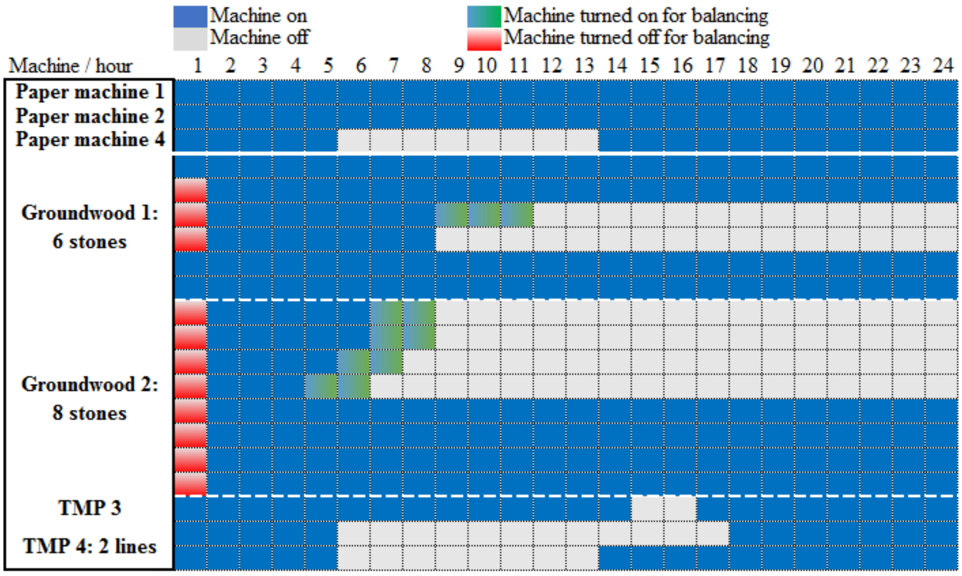

Figure 11. Production schedule in the regulating scenario in Case 1.

The original schedule was straightforward, and did not leave many intuitive possibilities for additional mass production. After the decreased production of hour 1, additional production is required for the equivalent of 3 hours for GW1 and 8 hours for GW2. The electricity required for this production can be purchased from the intra-day market or produced in the power plant. A combination of these strategies can, and in this case are used by the model. The intra-day price for the modeling period is presented in Figure 5.

This regulating scenario has no effect on the steam consumption of the mill site, because GW machines do not consume, or produce, any steam. Even though the steam consumption of the mill site is not affected by the regulating scenario, steam production and purchases may change due to changes in power plant production.

The extra production of GW1 is scheduled right after original production on the third stone. The same strategy with the fourth stone would have been effectively identical. An alternative approach could have been to continue production on both stones for 1 or 2 hours each. It is however seen from Figure 5, that there is a drop in the intra-day price of electricity on hour 11. It is thus optimal to only use one stone for the additional production.

The scheduling of additional production of GW2 can not be deduced similarly to GW1. Production is scheduled tightly as early as possible, with one exception. The stone 4 of GW2 is OFF on hour 7. This is due to a small constant added to the electricity consumption between stones 3 and 4 (see Section 7.1.1). This small difference combined with the minimal price difference between hours 7 and 8 causes production to be marginally (less than 1 €) more expensive on stone 4 on hour 7 than on stone 2 on hour 8. Stones 1 and 2 consume less electricity than stones 3 and 4. Production rates are equal for stones in the same groundwood line.

The hours and amounts of intra-day trading during the regulating scenario are shown in Table 2. It is noted that electricity is purchased on all hours of additional production, except for hour 10. During this hour, power plant production is increased with respect to the original scenario, instead. It is interesting to see that also during hour 19, there has been a 6 MWh electricity purchase from the intra-day market, even though there is no change in the mechanical mass production plan. The electricity is instead used to lower power plant production, decreasing its fuel consumption. This is due to the price of intra-day electricity being lower than the forecast price of spot electricity.

Table 2. List of hours when intra-day trading occurred in the regulating scenario of Case 1. Positive values denote purchases from the intra-day market.

Hour	5	6	7	8	9	11	19
Amount of trading (MWh)	1	3	5	3	1	1	6

The behavior described above is possible in the regulating scenario, but not in the base scenario. This results in a small additional benefit for the regulating scenario, as it can utilize the low intra-day price of electricity. This benefit is minimized through the constraints in Equations (33)–(36). Intra-day trading is not limited to hours with mass production schedules, because it would also limit the power plant's ability to optimize its production before and after hours of additional production. The overall benefit is moderate and it does not affect the comparability of the scenarios.

7.1.3 Cost difference between base and regulating scenarios

The regulating schedule is created based on the optimal schedule. This, together with intra-day electricity being pricier than spot electricity, means that the regulating schedule typically causes higher total costs than the base schedule. This price difference is used in this work to determine the cost of regulation. In the case of this section, the total costs are 123600 € and 125500 € for the base and regulating schedule, respectively. Thus, the cost of regulation is 1900 € or 95 €/MWh. Causes for the cost difference are listed in Table 3. The greatest single cost addition in the regulating schedule is the increased penalty cost. This increase corresponds to the start-up costs of 11 mechanical mass production lines on hour 2. These lines were turned OFF on hour 1 to execute the regulating bid. Another addition is the intra-day electricity purchases. Purchases of steam have not changed in the regulating schedule. Fuel costs have increased slightly due to changes in electricity production needs.

Table 3. Cost difference analysis of base and regulating scenario total costs.

Variable (€)	Optimal scenario without regulation	Regulating scenario	Difference
Total cost of operation	123600	125500	1900
Intra-day purchase cost	0	630	630
Fuel cost	38210	38380	170
Steam purchases	13220	13220	0
Penalty costs	450	1550	1100

7.2 Case 2: Comparison of two alternative schedules

In Case 1, an optimal mechanical mass production schedule was created with the model. A regulating scenario was also made based on the optimal schedule. In this section, a regulating power bid is manually input to the model. The model is then used to optimize the schedule for additional production. Next, the another schedule is modeled with a manually chosen schedule for additional production. This is achieved through minor changes in the model that are left undocumented in this work. The differences between the two schedules, the optimal and manual schedule, are analyzed.

7.2.1 Optimal regulating schedule

The optimal regulating schedule is shown in Figure 12. Here, 27 MWh of regulating power has been sold to the grid on hour 1. Additional production has been scheduled for hours 18, 23 and 24. Prices of electricity for the modeling period are shown in Figure 13. The intra-day price is low during the hours 1–5, rising quickly to 40 €/MWh and remaining on and over this level until hour 21, after which it decreases again. Hours 23–24, which were chosen for additional production of GW1, have a relatively low price of intra-day electricity in comparison with the peak hours. The price levels of hours 6, 13, and 16 are the same, which creates a lot of low-priced flexibility for additional TMP4 production. Additional costs may come from the cost of steam and possible start-up costs.

7.2.2 Manual regulating schedule

The manual schedule is presented in Figure 14. When compared to the optimal schedule, it is seen that all additional production has been moved to begin as early as possible. This is seen as a logical alternative schedule. Next, the optimal and manual schedules will be compared with each other.

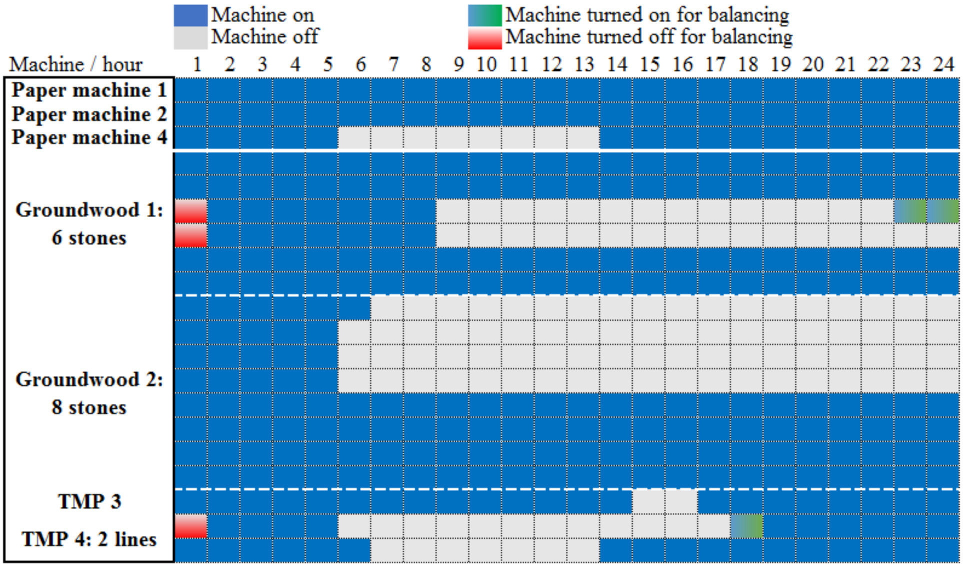

Figure 12. Schedule of the optimal additional production in regulating power scenario in Case 2.

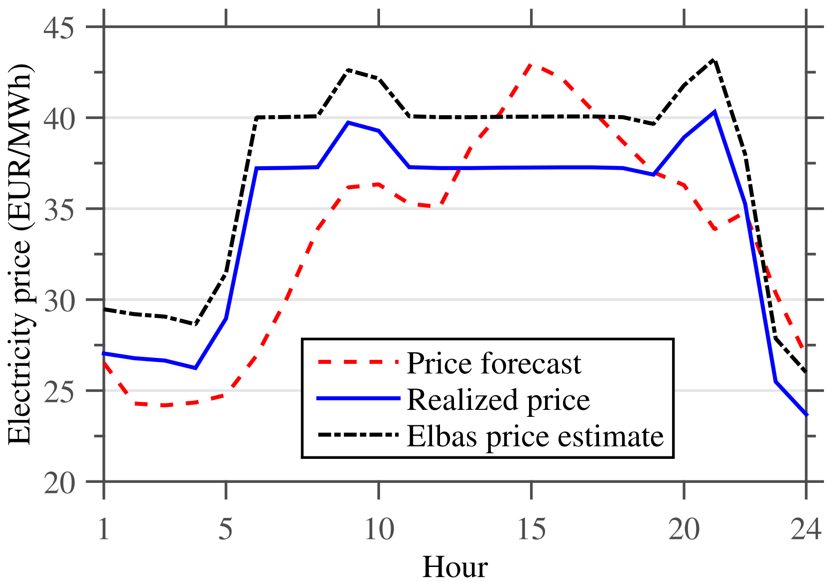

Figure 13. Prices of electricity in Case 2.

In Table 4, hourly differences are shown between the variables of the optimal and manual schedules. If the value of a variable is higher in the manual schedule, it will appear in the table as a positive value. The values are rounded, and only notable differences are listed. In the following analysis, in the favor of readability, the differences of the schedules are described as if optimal production were changed to the manual schedule.

It is seen from Table 4 that in the hours from which mass production was removed (18, 23, 24) there are generally higher steam purchases and lower heat production in

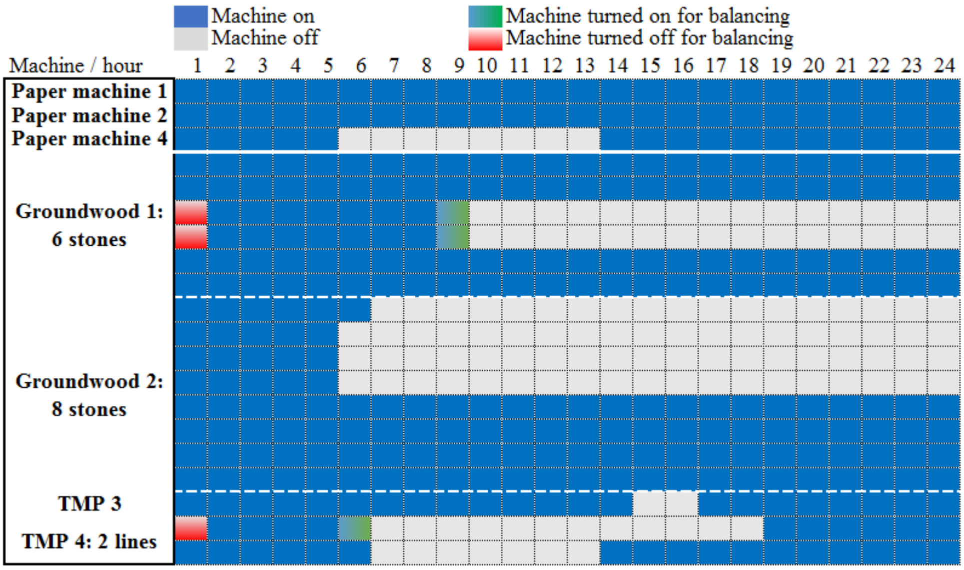

Figure 14. Manual schedule of additional production in Case 2.

the manual schedule than in the optimal one. Electricity production changes in the same direction as heat production. This can be explained as follows: in the optimal schedule, the electricity required for additional mechanical mass production is secured partially by intra-day purchases and partially by increased production. As a side product of increased electricity production, the economic heat production increases, which decreases the need for purchased steam. When in the manual schedule the economic electricity production is lower (no additional mechanical mass production), the amount of purchased steam is higher. This underlines what was found in the analysis of Case 1, that the produced and purchased amounts of steam and electricity have a relationship that is difficult to describe analytically.

Hours 6 and 9 are timesteps to which production is added when changing from the optimal schedule to the manual one. It is seen from Table 4 that the changes in values are consistently of the opposite sign to hours already analyzed above.

Venting of steam is affected by the change of schedule. It is seen that when additional production of TMP4 is moved from hour 18 to hour 6, the total venting of steam increases. This shows that even though the electricity prices of the hours are close

Table 4. Notable changes from the optimal to the manual schedule in Case 2.

Change in variable (MWh)	Hour 4	5	6	9	18	22	23	24
Steam purchased	−1	−1	−1		−2	+1	+13	+2
Heat produced	+1	+1	+3		+11	−1	−13	−2
Electricity produced			+1		+3		−4	−1
Intra-day el. purchased			+13	+13	−17		−3	−6
Steam vented			+15		−5			

Table 5. Cost differences between the optimal and manual production schedules in Case 2.

Variable (€)	Optimal regulating scenario schedule	Manual regulating scenario schedule	Difference
Total cost of regulation	1360	1590	230
Intra-day purchase costs	920	1070	150
Fuel costs	32140	32160	20
Steam purchases	3180	3310	130
Penalty costs	1040	970	−70

to each other, the steam balance may make one hour notably more economic than the other.

Hours 4, 5 and 22 are listed, even though there are no changes of schedule on them. The changes are limited to purchases and production of steam, and are due to the limitations in the rate of change of steam purchases. The model adapts to the future needs on these hours.

7.2.3 Cost difference between the schedules

The total operating cost (see Equation (42)) of the mill site for the schedule of the optimal regulating scenario is 135100 €. The corresponding cost for the manual schedule is 135300 €. The cost of the optimal schedule without regulation is 133700 €. Thus, the optimal and manual regulating schedules cause costs of 1360 and 1590 €, respectively. Considering the size of the regulating bid, this equals to 50 and 59 €/MWh for the optimal and manual regulating schedule, respectively. The causes of this difference are detailed in Table 5.

For a large part, the difference in costs between the schedules comes from additional intra-day electricity purchases and additional steam purchases. The total volume of intra-day purchases is the same in both schedules, but the price level is higher in the manual one. The total consumption of steam is higher in the manual schedule. This is due to increased venting of steam, which increases the penalty costs of the model. Penalty costs also include the start-up costs of machines. The penalty costs of the manual schedule are lower than in the optimal schedule, because one start-up is averted. Fuel cost difference between the schedules is small, despite notable changes in the temporal distribution of heat and electricity production.

7.3 Analysis of multiple modeling runs

In Case 1, the model was used to create optimized production schedules and corresponding regulating schedules. Next, that same method is used for a mass run to analyze the correlations between the modeling period parameters and the calculated cost of regulation. Time-dependent parameters, i.e. the forecast and realized spot price of electricity, the DH demand, and the amount of sold steam, are used to run the model in different set-ups. Other parameters remain constant throughout this analysis. The parameters of this case are different from Cases 1 and 2.

The model is run with the parameters from starting at 3 a.m. and 10 a.m. each day of year 2014. This makes 730 runs. The regulating power bid is limited to 20–25 MWh of up-regulation during hour 1. This is not always possible due to a lack of originally scheduled mechanical mass production. There are 697 runs in which the regulating power bid is possible to create. Other 33 runs are excluded from analysis.

In Figure 15, the cost of regulation on each analyzed model run is shown, along with the corresponding modeling period's average realized spot price. The majority of spot prices are under 50 €/MWh, and the clear majority of regulating prices are under 100 €/MWh. There is some correlation between average spot price and the cost of regulation, which is expected. The price of intra-day electricity, which is calculated from the spot price, directly affects the cost of regulation. It is difficult to quantify the relationship between the cost of electricity and the cost of regulation from the figure.

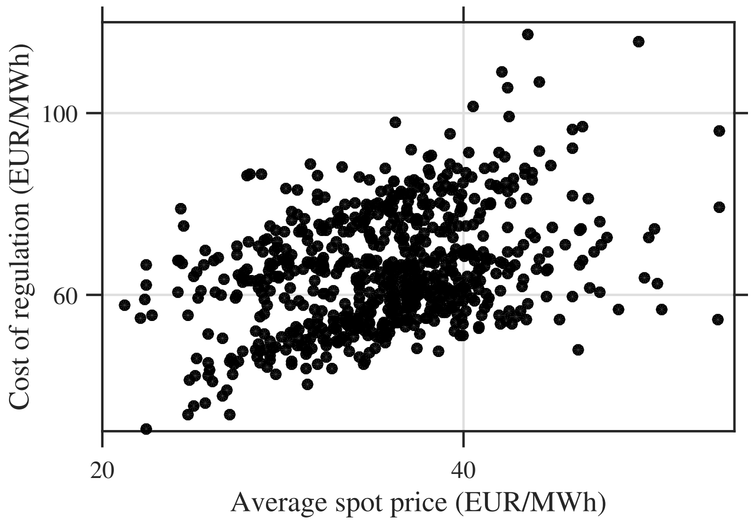

Figure 15. The cost of regulation and average spot price of each run of the model.

Figure 16 presents a histogram of the values of the cost of regulation divided by the average price of electricity for the modeling period. The peak of occurrences between the values 1.4 and 1.8 indicate that in over 300 of nearly 700 runs, the cost of regulation is 1.4–1.8 times more expensive than average spot electricity during the modeling period. Similarly, in the clear majority of all runs, the price of regulation is 1.4–2.4 times more expensive than the average spot price.

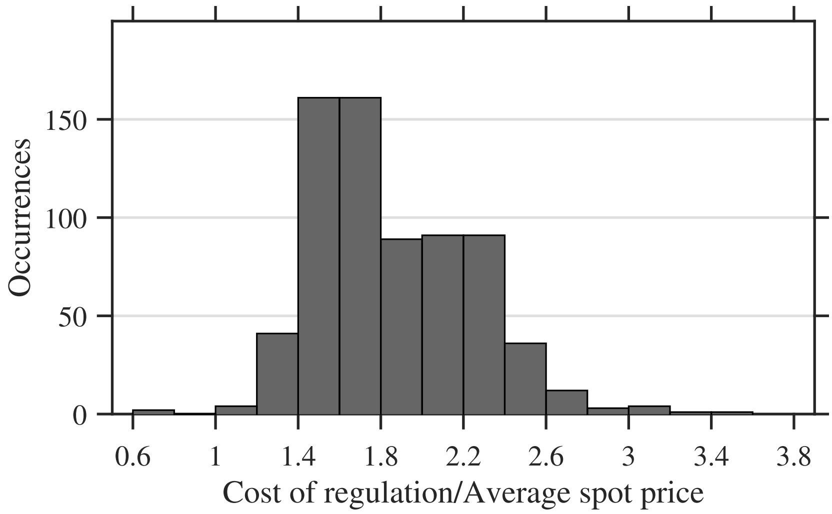

Figure 16. Histogram of relative costs of regulation in the model runs.

The model chooses whether to produce or purchase the electricity required for additional production after regulating hours. In Figure 17, the procurement strategy of electricity is shown for the additional mechanical mass production of each analyzed run. Lines are also shown that illustrate the area where the total procurement of additional electricity would be in the range of the allowed size of the regulating power bid. The runs have different amounts of regulation. It is seen that additional electric power is mainly purchased from the intra-day market. Own additional production is used, but to a lesser extent. Most often both alternatives are utilized.

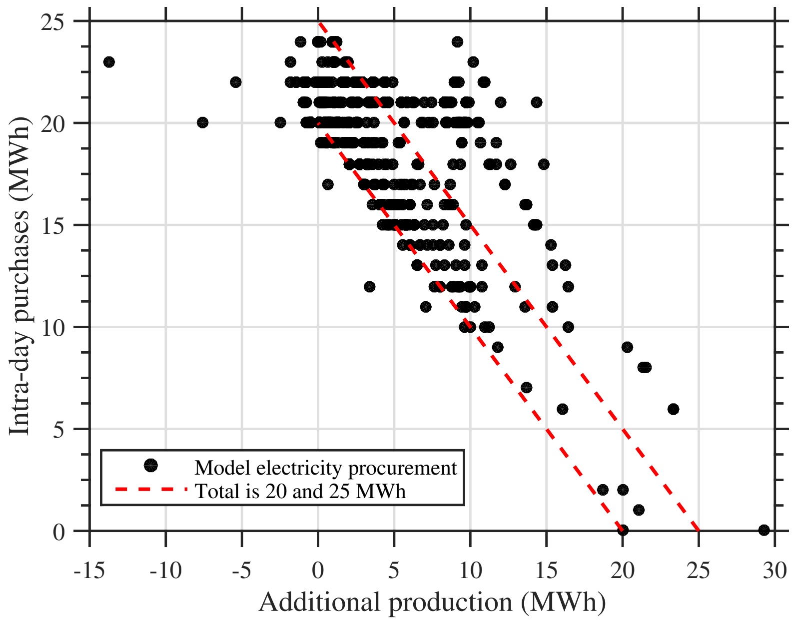

Figure 17. The procurement of electricity for additional mechanical mass production.

Intra-day purchases are made in integer amounts, which shows as non-continuity in values on the corresponding axis. The data has a clear and natural correlation: The more own additional production, the less there is need for intra-day purchases. In the majority of cases the procurement of electricity sums up to roughly the amount of regulation. However, if large changes are made in the machinery used for mechanical mass production, the total electricity consumption of the site may change notably. In the figure this may show as points where the total procurement of electricity is notably more or less than the maximum or minimum amount of regulation, respectively. Some of these extremal values result from the optimality gap and time limit used in solving the MILP model (see Section 5.6).

Further analyses could be made on the basis of these results. The analyses could be used for identifying trends in the results and for improving the details of the model.

8 Conclusions

In this Thesis, a MILP model was created of a paper mill site with mechanical mass and paper production, and an integrated CHP power plant. The model creates optimized mechanical mass production schedules for the site, simultaneously optimizing the energy management of the mill, including the operation of the CHP plant. Balances considered in calculations are electricity, DH, three different pressure levels of steam, and all types of mechanical mass produced in the mill. The model only considers the processes and machines that notably influence the flexibility of the mill site.

The model was extended to create regulating power scenarios for the mill site. Both up- and down-regulating scenarios are supported, for one or several hours. In these scenarios, the model will halt or start production in a suitable combination of mechanical mass production lines during the regulating hours. The allowed combinations are affected by parameters. The deficit or surplus of mechanical mass caused by regulation is corrected during the rest of the modeling period. This causes subsequent halts or starts of production, which in turn lead to electricity imbalances. These can be corrected with production plan changes of the CHP plant, or through intra-day trading of electricity. The model will combine schedule and energy management plan changes so that additional costs are minimized, while all requirements are fulfilled.

The model results were realistic in all aspects of the model, including the scheduling of mechanical mass production, the use of storage towers and the costs of executing regulating power bids. The results illustrate the complexity of optimizing the scheduling of mechanical mass production simultaneously with the energy management of the whole mill site. The results often include situations where the price of electricity or need of steam alone do not define the scheduling of production.

The objective of this Thesis was to study the flexibility of mechanical mass production, the potential for co-planning of mechanical mass and CHP production, and the costs of executing regulating power bids with the mill site. In this respect, the work was successful. The flexibility of mechanical mass production was modeled, and it was scheduled simultaneously with CHP production planning. The costs of executing regulating power bids were also calculated. The model allows improved understanding of the dependencies between different processes in the mill site.

From the results, it was noted that in regulating power scenarios, all changes in mechanical mass production lead to changes also in CHP production. The power plant removes imbalances caused by the combinations of intra-day trading and changes in consumption, and also lowers the need for intra-day trading. In the model, the co-operation between the processes is of course ideal. However, the level of co-operation of the pulp and paper mill and the power plant is less explored in the real case site. This could be analyzed in more detail, both through the model and in the case site, to estimate the potential improvement that could be reached by working on improving the described type of co-operation.

The model presented in this Thesis has provided experience and understanding of the processes that limit and create the flexibility of the mill site as a whole. In the future, however, there are a number of possibilities of extending and improving the model. Some areas of improvement are:

- A more accurate power plant model, considering different boilers and fuels along with their costs
- Implementing reject handling into the model, as well as the high powered pumps moving mechanical mass between storages
- Adding the optimization of paper production scheduling into the model

Naturally, improving the model is only a step towards real life improvements. To benefit from this work, the case company should increase their understanding of optimization, implement operational optimization tools, and finally mobilize a change management project that aims at improving the co-operation and co-planning of mechanical mass and CHP production.

References

[1] De Menezes, L. M. and Houllier, M. A. 2015. Germany's nuclear power plant closures and the integration of electricity markets in Europe. *Energy Policy* Vol. 85. Pp. 357–368.

[2] International Energy Agency. 2015. *World energy Outlook Special Report: Energy and Climate Change.*

[3] Victor, D. G. et al. 2014. *Introductory Chapter. In: Climate Change 2014: Mitigation of Climate Change.* Cambridge University.

[4] Bruckner, T. et al. 2014. *Energy Systems. In: Climate Change 2014: Mitigation of Climate Change.* Cambridge University.

[5] The European Wind Energy Association. 2015. *Wind in power: 2014 European statistics.*

[6] Bang, C., Fock, F., and Togeby, M. 2012. *The existing Nordic regulating power market.* Ea Energy Analyses.

[7] Pöyry. 2014. *Sähkön kysyntäjoustopotentiaalin kartoitus Suomessa.* URL: http://www.fingrid.fi/fi/sahkomarkkinat/markkinaliitteet/Kysynt\%C3\%A4jousto/Fingrid_Julkinen_raportti_kysynt\%C3\%A4jousto_16062014.pdf (Retrieved 16.9.2015).

[8] Fingrid Oyj. 2015. *Kysyntäjousto.* URL: http://www.fingrid.fi/fi/sahkomarkkinat/Kysyntajousto/Sivut/default.aspx (Retrieved 8.9.2015).

[9] Lindberg, C.-F. et al. 2014. Potential and Limitations for Industrial Demand Side Management. *Energy Procedia* Vol. 61. Pp. 415–418.

[10] Ruohonen, P. and Ahtila, P. 2011. Qualitative analysis of a thermo mechanical pulp and paper mill using advanced composite curves. *Energy* Vol. 36:6. Pp. 3871–3877.

[11] Ruohonen, P. et al. 2010. Analysis of alternative secondary heat uses to improve energy efficiency–case: A Finnish mechanical pulp and paper mill. *Resources, Conservation and Recycling* Vol. 54:5. Pp. 326–335.

[12] Kong, L. et al. 2015. Energy conservation and CO_2 mitigation potentials in the Chinese pulp and paper industry. In press. *Resources, Conservation and Recycling.*

[13] Jönsson, J. et al. 2011. The potential for steam savings and implementation of different biorefinery concepts in Scandinavian integrated TMP and paper mills. *Applied Thermal Engineering* Vol. 31:13. Pp. 2107–2114.

[14] International Energy Agency. 2007. *Tracking Industrial Energy Efficiency and CO_2 Emissions.*

[15] Merkert, L. et al. 2015. Scheduling and energy – Industrial challenges and opportunities. *Computers & Chemical Engineering* Vol. 72. Pp. 183–198.

[16] Figueira, G. et al. 2015. A decision support system for the operational production planning and scheduling of an integrated pulp and paper mill. *Computers & Chemical Engineering* Vol. 77. Pp. 85–104.

[17] Santos, M. O. and Almada-Lobo, B. 2012. Integrated pulp and paper mill planning and scheduling. *Computers & Industrial Engineering* Vol. 63:1. Pp. 1–12.

[18] Figueira, G., Santos, M. O., and Almada-Lobo, B. 2013. A hybrid VNS approach for the short-term production planning and scheduling: A case study in the pulp and paper industry. *Computers & Operations Research* Vol. 40:7. Pp. 1804–1818.

[19] Sarimveis, H. et al. 2003. Optimal energy management in pulp and paper mills. *Energy Conversion and Management* Vol. 44:10. Pp. 1707–1718.

[20] Lahdelma, R. and Hakonen, H. 2003. An efficient linear programming algorithm for combined heat and power production. *European Journal of Operational Research* Vol. 148:1. Pp. 141–151.

[21] Ait-Ali, A. 2015. Integration of Production Scheduling and Energy Management : Software Development. MA thesis. KTH, Optimization and Systems Theory.

[22] Prowledge Oy. 2013. *Knowpap 16.0, e-Learning Environment for Papermaking and Automation*.

[23] Nord Pool Spot. 2015. *A powerful partner: Annual Report 2014*.

[24] Partanen, J. et al. 2008. *Sähkömarkkinat - opetusmoniste*. Lappeenrannan teknillinen yliopisto, sähkötekniikan osasto.

[25] *Nord Pool Spot*. 2015. URL: http://www.nordpoolspot.com/ (Retrieved 8.9.2015).

[26] *Fingrid - regulating power market*. URL: http://www.fingrid.fi/en/customers/Balance\%20services/management/powermarket/Pages/default.aspx (Retrieved 9.9.2015).

[27] Rong, A., Lahdelma, R., and Grunow, M. 2009. An improved unit decommitment algorithm for combined heat and power systems. *European Journal of Operational Research* Vol. 195:2. Pp. 552–562.

[28] Makkonen, S. and Lahdelma, R. 2006. Non-convex power plant modelling in energy optimisation. *European Journal of Operational Research* Vol. 171:3. Pp. 1113–1126.

[29] UPM Kymmene Oyj. 2015. *Internal document (unpublished)*.